METHODOLOGY TO OPTIMIZE FOR PEDESTRIAN DELAY AND VEHICULAR DELAY IN A SIGNAL NETWORK

A Thesis
Presented to
the Faculty of the Graduate School
University of Missouri-Columbia

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

---

by
PRABHATI BHATTACHARYA

Dr. Mark R. Virkler, Thesis Supervisor

DECEMBER 2004

The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

METHODOLOGY TO OPTIMIZE FOR PEDESTRIAN DELAY AND VEHICULAR DELAY IN A SIGNAL NETWORK

presented by Prabhati Bhattacharya

a candidate for the degree of Master of Science

and hereby certify that in their opinion it is worthy of acceptance.

Dr. Mark R.Virkler

Dr. Carlos C. Sun

Dr. James S. Noble

ACKNOWLEDGEMENTS

I am grateful to many individuals for their assistance during the course of this project.

First, I specially thank my advisor, Dr. Mark R. Virkler for his continuous effort and guidance during the research and preparation of this thesis. I also thank Dr. Carlos C. Sun for his recommendations to the research and Dr. James S. Noble for being present on my Master's Thesis Committee. In addition, I thank the Midwest Transportation Scholars Consortium Program for providing the financial support that made this investigation possible.

I dedicate this work to my family; whose constant encouragement, understanding and moral support played an important role through the course of this work. Especially to my parents whose love has supported me throughout. Last but not the least; I thank my friends for their moral support and loving friendship.

ABSTRACT

Efficiency of an arterial network could be enhanced by optimizing the user costs of the network incurred due to delay and other socio-economic factors. Until recently, research mostly focused on minimizing vehicular delay to optimize user costs. Currently no tool exists to balance delays to both vehicles and pedestrians. This research developed a methodology that employed known techniques and available tools to identify optimal signal co-ordination plans. The optimal signal timings determined can minimize the total delay to both vehicles and pedestrians. Pedestrian delay patterns were obtained from previous research. Delay data for vehicles was based on modeling peak-hour traffic conditions in urbanized areas of a hypothetical city. The signal optimization software Synchro Version 3.2 was used to investigate the variations in vehicle delay with different signal coordination plans and offsets. Delays to vehicles and pedestrians with respect to various offsets were analyzed. The results evinced that the best offsets for vehicles and pedestrians were not necessarily the same. Consequently a signal coordination plan to benefit both should consider the total user costs of the system. Higher user costs could be encountered if pedestrian progression was not considered and only vehicles were considered. Results showed that the highest total pedestrian delay could spike up the user costs more than the highest total vehicular delay. The offset generating the optimal user cost could be different from the best offset for vehicles or pedestrians. A balance could be achieved between pedestrian delay and vehicular delay to arrive at an optimal signal coordination plan. Significant implications of such a trade-off are discussed in view of current transportation trends.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS…………………………………………………………ii

ABSTRACT………………………………………………………………………iii

LIST OF TABLES……………………………………………………………...vi

LIST OF FIGURES…………………………………………………………...viii

Chapter

1. INTRODUCTION…………………………………………………………1

1.1 Problem Statement……………………………………………….......1
1.2 Objective…………………………………………………………...2
1.3 Contribution towards Arterial Traffic Management ……………..3
1.4 Thesis Organization………………………………………………….3

2. BACKGROUND ………………………………………………………….5

2.1 Progression……………………………………………………………...5
2.1.1 Vehicles
2.1.1.1 Undersaturated versus Oversaturated Flow Conditions
2.1.2 Pedestrians
2.1.2.1 Pedestrian Speed Variability
2.1.2.2 Platooning
2.2 Network Modeling……………………………………………..24
2.3 Travel Time Costs and Relative Values of Travel Time…………26
2.4 Transportation Modal Patterns……………………………………28

3. DEVELOPMENT OF METHODOLOGY FOR OPTIMIZATION OF PEDESTRIAN DELAY AND VEHICULAR DELAY………………….30

3.1 Site Selection……………………………………………………...30
3.2 Description of Required Data……………………………………...35
3.3 Methods and Techniques…………………………………………..36

4. CASE STUDY : AN APPLICATION OF THE METHODOLOGY….43

4.1 Design of Case Study………………………………………………43
4.1.1 Site Characteristics
4.1.2 Field Set-up on Synchro 3.2
4.1.3 Procedures and Assumptions
4.2 Results of Case Study……………………………………………...53
4.3 Discussion on Results……………………………………………...83

5. CONCLUSIONS AND FUTURE RESEARCH……………………… 84

5.1 Inferences on Case Study……………………………………….. 84
5.2 Discussion on Methodology…………………………………….. 84
5.3 Conclusions……………………………………………………… 85
5.4 Contributions……………………………………………………. 86
5.5 Future Research…………………………………………………. 87

REFERENCES……………………………………………………………… 95

APPENDIX A: DETAILS OF SYNCHRO MODELING AND OPTIMIZATION………………………………………………... 98

APPENDIX B: DESCRIPTION OF RESULTS FROM ANALYSIS…………… 106

LIST OF TABLES

TABLE 2-1: Progression adjustment factor (PF) given in HCM 2000…………………17

TABLE 3-1: Data required to apply the methodology……………………………….36

TABLE 4-1: Vehicle input volumes and pedestrians conflicting with turning Movements…………………………………………………………..55

TABLE 4-2: Individual delay to vehicles with change in offset (from Synchro)………56

TABLE 4-3: Delay to pedestrians with change in offset……………………………….57

TABLE 4-4: Phase splits resulting from modeling on Synchro………………………..58

TABLE 4-5: Network vehicle delay for each offset combination……………………...59

TABLE 4-6: Network pedestrian delay varies with the offset…………………………60

TABLE 4-7: Comparison of network pedestrian delay and vehicle delay…………….61

TABLE 4-8: Network user cost determined (Pedestrian delay valued as twice the vehicle delay)………………………………………………………….64

TABLE 4-9: Network user cost considering relative values of travel time…………..67

TABLE 4-10: Vehicle input volumes and pedestrians conflicting with turning movements………………………………………………………….68

TABLE 4-11: Individual delay to vehicles with change in offset (from Synchro)….69

TABLE 4-12: Phase splits optimized by modeling on Synchro ……………………..70

TABLE 4-13: Network vehicle delay for various offset combinations………………70

TABLE 4-14: Network pedestrian delay for various offset combinations……………71

TABLE 4-15: Comparison of network total pedestrian delay and vehicle delay…….72

TABLE 4-16: Determination of user costs (pedestrian delay valued equally as vehicle delay)………………………………………………………….77

TABLE 4-17: Input data for model analysis 1 with high vehicle volumes…………..79

TABLE 4-18: Input data for model analysis 2 with low vehicle volumes…………..81

TABLE B-1: Input volumes for modeling Scenario 1……………………………...106

TABLE B-2: Individual vehicle delays as modeled by Synchro…………………...107

TABLE B-3: Determination of user costs for various offsets……………………...109

TABLE B-4: Computation of delay ratio for increasing v/C ratios ………………..115

LIST OF FIGURES

FIGURE 2-1: A case study to show one-way alternate progression…………………..11

FIGURE 2-2: A case study to show one-way double alternate progression…………..12

FIGURE 2-3: A case study to show one-way simultaneous progression……………...13

FIGURE 2-4: An example to illustrate two-way alternate progression……………….14

FIGURE 2-5: Field set-up to study arterial progression………………………………18

FIGURE 2-6: Characteristics of vehicle progression as demand increases…………...20

FIGURE 2-7: Flow rate at downstream signal approach versus time in upstream signal cycle……………………………………………………………..24

FIGURE 3-1: Pedestrian movement on a typical urban street ………….…………….31

FIGURE 3-2: Overview of methodology……………………………………………..34

FIGURE 4-1: A view of the study network…………………………………………..46

FIGURE 4-2: Flows within a typical intersection in the corridor……………………47

FIGURE 4-3: Network total vehicle delay and pedestrian delay variation with offsets……………………………………………………………62

FIGURE 4-4: User cost in the network varies with the offset between nodes………65

FIGURE 4-5: Variation in total pedestrian and total vehicle delay with change in offset………………………………………………………………73

FIGURE 4-6: Comparison of total delay values for varying pedestrian volumes…..74

FIGURE 4-7: Comparison of user cost with different offsets for varying pedestrian volumes………………………………………………75

FIGURE 4-8: Effect of increasing pedestrian volumes on the user cost for different offsets…………………………………………………………76

FIGURE 4-9: Comparison of user costs based on relative valuation of pedestrian delay and vehicle delay………………………………………………78

FIGURE 4-10: Comparison of Synchro progression and HCM progression by delay adjustment factor (peak traffic)……………………………80

FIGURE 4-11: Comparison of Synchro progression and HCM progression by delay adjustment factor (off-peak traffic)……………………….82

FIGURE A-1: Illustration of the case study network in Synchro………………102

FIGURE A-2: View of the lane input window in Synchro……………………..103

FIGURE A-3: View of the traffic volumes window in Synchro…………….….104

FIGURE A-4: Arterial report window displaying various output flow measures…………………………………………………..….105

FIGURE B-1: Variation of total delay to pedestrians and vehicles with change in offset……………………………………………………….108

FIGURE B-2: Variation of user costs with offset……………………………….110

FIGURE B-3: Comparison of total pedestrian delay and total vehicle delay for various offsets for the third scenario…………………………111

FIGURE B-4: User costs with various offsets for 100 pedestrians per hour…….112

FIGURE B-5: Effect of increasing pedestrian volumes on vehicle delay for different offsets……………………………………….……113

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Traffic signal systems are set up along urban corridors to control the flow of traffic. During peak hours, a corridor may operate under moderate traffic flow with no serious congestion. However, travelers may experience excessive delay at intersections due to lack of signal coordination. Sometimes high flows of both pedestrians and vehicles along the corridor may create congestion problems. Traffic congestion on urban streets leads to widespread network delays. The capacities of urban streets are generally contingent on traffic signal control settings. However, according to Benekohal et al. (2000), loss of a major proportion of the potential capacity can occur if the signals are not properly coordinated. The conventional idea of estimation of arterial capacity from the capacities of signalized intersections does not totally comply with oversaturated conditions. An increasing population of urban traffic engineers find themselves in a conundrum when having to analyze traffic situations with competing modes of transportation. Signal optimization and signal coordination strategies have been found to be effective in alleviating congestion, where physical changes in the network environment to enhance progression would not be feasible. A major concern is that of signal design without proper planning and consideration of the geometric and flow characteristics of the network. Apportioning appropriate green time to traffic signal phases in the intersection with proper signal coordination is a vital task for traffic engineers.

Ensuring good progression for both vehicles and pedestrians along a signalized route could prove to be a difficult task. Among other factors, delays induced by the operation of traffic signals constitute a significant proportion of the total travel time of pedestrians or vehicles on these routes.

1.2 Objective

The aim of this research was to devise a methodology to provide for both pedestrian and motor vehicle progression along important pedestrian signalized routes. For a network comprising several links, the method considered traffic improvement strategies using signal coordination. The research focused on the development of a model that would aid transportation professionals in making key decisions related to signal coordination. This research also investigated the delay patterns resulting through various signal coordination plans. A case study demonstrates the methodology developed. A framework is established based on pedestrian and vehicle travel characteristics during peak hours to minimize the network delay. The method is designed for streets in central business district areas or urban arterials during peak traffic conditions. The paper presents a model to quantify the benefits of progression through the computation of delay costs.

The field site could be an urban arterial, an urban street in a central business district area, a major thoroughfare with places of interest such as theatres, cinema halls and stadiums or any network with peak traffic at certain times of the day or week. The issues involved in the investigation are the socio-economic aspects of comparing the value of pedestrian delay to vehicle delay. Pedestrians travel at a comparatively lower speed than vehicles. Walking may constitute part of an automobile trip, depending on perspective. These issues and concerns need to be considered while comparing delays to various modes and their relative importance. The research assayed the benefits of progression through the determination of an optimal signal coordination plan. The goal was to increase opportunities for favorable progression on busy urban corridors.

1.3 Contribution towards Arterial Traffic Management

The explosive vehicular volume growth on major arterials is a major problem faced by many metropolitan areas in the United States, according to a report by Reid et al. (1999). There has been a steady increase in vehicle miles traveled (VMT) during the past few decades. Heightened freeway congestion and expanded urban centers have increased the traffic-carrying importance of major arterials. This signifies that these arterials need to carry more long-distance vehicle trips and greater volumes. HCM 2000 contains guidelines for estimation of intersection capacity but not arterial capacity. A literature study revealed various extant strategies to control oversaturated signalized arterials. Traffic engineers should enhance the ability of roadway designs and traffic signal systems to progress traffic along urban arterials. This research presents some directions to optimize traffic delay and enhance throughput on an arterial by providing proper signal coordination.

1.4 Thesis Organization

The thesis is organized into five chapters. The first chapter provides a broad overview of the research problem with a description of the objective and probable contribution to current body of knowledge. The second chapter discusses the background of the study in conjunction with key principles and rationales. Definitions and terms used are explained in reference to the research problem. The central idea of the research is the development of a methodology to address the problem. This comprises the content of the third chapter. The fourth chapter describes in detail a case study to demonstrate the application of the methodology developed in the third chapter. The results of the case study are discussed in the context of research. The last two chapters summarize the findings and state the conclusions the results support along with suggestions for further research. Appendix A and Appendix B towards the end of the thesis contain supplementary figures and tables to explain the case study in Chapter 4 and some information on the traffic modeling software Synchro 3.2.

CHAPTER 2

BACKGROUND

This chapter presents a background to the study approach. The principal considerations for pedestrian and vehicular progression are discussed, including progression types and techniques as defined in the Highway Capacity Manual. Correspondingly, pedestrian speed characteristics and platooning are conceptually described. The concluding sections of the chapter describe the significance of the choice of a suitable traffic software model and relevant relative values of travel time in the methodology.

2.1 Progression

Progression can be defined as a benefit of signal coordination. Achieving good progression is generally the primary purpose of providing signal coordination on an arterial or corridor. Good progression can be described as minimization of stops and delays to travelers traveling along the arterial. If the signal spacing is 350 feet, and vehicles are traveling at a speed of 30 miles per hour (44 feet per second), then very good vehicular progression can be attained by setting an 8 second offset between the signals. If pedestrians commute at a speed of 4 feet per second on the same street, an offset of about 12 seconds (accompanied by a 75 second cycle length at the pedestrian-signalized intersections) would benefit pedestrian progression. It is possible to formulate an expression to find the optimum offset for delay minimization in terms of the modal speed, block length and signal cycle at the upstream intersection. To apply a given signal coordination plan, a similar expression can enable planners to identify block lengths in accord with the plan. These considerations can assist the traffic control agency or engineer in adjusting offsets between arterial signals. However, several factors limit the benefits of signal coordination. Some of these factors are interrelated. The factors are listed as follows:

- Capacity of the roadway is inadequate
- Substantial side frictions, including parking, loading, driveways are present
- Intersections are complex with multiphase signal control
- Traffic speeds vary widely
- Signal spacing is too short (less than 300 feet)
- Turning volumes are quite high (exceed 30% of main street through volume)

Elements favorable for progression and implementation of signal coordination include flow and intersection geometry as stated below:

- Relatively uniform and short signal spacing
- Vehicles move downstream in an intact platoon
- Higher proportion of through vehicles than turning vehicles (at least 80% of the approach volume)

The bandwidth maximization approach facilitates the traffic engineer in visualizing the progression and provides a perceptible view of progression along the arterial. It comprises some simple visual techniques to plan for favorable progression along two-way arterial streets. In their simplest forms, these techniques assume uniform block lengths and a relevant relationship among the block length, progression speed and cycle length.

In the subsequent paragraphs, some of these techniques are explained and an attempt is made to illustrate each technique with relevant figures and design calculations. For further details on the concept, Prassas et al. (2002) can be consulted.

- **Alternate Signal Progression**

This type of progression is suitable for streets with certain uniform block lengths. The ideal offset in either direction between consecutive intersections is the travel time between the two intersections. If the signal timing at all intersections is designated with 50:50 splits, the sum of the desired two offsets adds up to the cycle length. The bandwidth attained by vehicles equals one-half of the cycle length. An illustration of this technique is given in Figure 2-1. From Figure 2-1, a bandwidth equivalent to half a cycle length is observed for vehicles at operating speeds as shown below:

$$S_A = L / (C/2)$$

where: C = cycle length (seconds)

L = block length (feet)

S_A = platoon speed (feet per second)

To apply travel speeds in miles per hour, a conversion factor of 1.466 can be used to convert miles per hour to feet per second as shown below:

$$1.466 * S_A = L / (C/2)$$

$$\text{or, } S_A = (2*L) / (C*1.466)$$

S_A = platoon speed (miles per hour)

1.466 = Conversion factor (to convert speed in miles per hour to feet per second)

For instance, if the block lengths are about 1320 feet (one-fourth of a mile) with vehicles moving at 30 miles per hour, a cycle length of 60 seconds would favor progression. At lower speeds, longer cycle lengths are feasible for a given block length. Furthermore, at a given posted speed, as the block length increases, larger cycle lengths are favorable for progression.

Pedestrians move at lower speeds of about 3 miles per hour (or 4 feet per second). The dotted lines in Figure 2-1 represent pedestrian trajectories. For a bandwidth equivalent to half the cycle length, the favorable progression speed would be as shown:

$S_P = (2*L) / (7*C)$

Accordingly, for a block length of 1320 feet and pedestrians moving at 4 feet per second, cycle lengths of about 90 seconds would be ideal for progression. In brief, the bandwidth optimization approach suggests that to ensure progression to both vehicles and pedestrians given that the link lengths are about quarter of a mile, the cycle lengths should ideally be in the range of 60 seconds to 90 seconds.

- **Double Alternate Signal Progression**

In this type of progression, the ideal offset in either direction over two blocks is set equivalent to the travel time along two consecutive blocks. For 50:50 splits, the travel time of each platoon along two consecutive blocks is one-half of a cycle length. A bandwidth of one-quarter of a cycle length can be achieved. Figure 2-2 provides instances of vehicle and pedestrian trajectories under this technique.

The technique yields cycle lengths favorable for vehicle progression under the given operating conditions as below:

$1.466 * S_A = L / (C/4)$

or, $C = (4* L) / (S_A * 1.466)$

where all terms are as previously defined.

Given L = 1000 feet, S_A= 30 miles per hour, cycle length favorable for progression due to maximum bandwidth would be approximately 94 seconds. For pedestrians, Figure 2-2 indicates that a good bandwidth could be achieved in the following set-up:

$$S_P = L / (4 * C)$$

$$C = L / (S_P * 4)$$

If pedestrians travel at a speed of 4 feet per second on a block length of 1000 feet, then a favorable cycle length would be 62 seconds. To achieve double alternate progression, the desirable range of cycle lengths for both vehicle and pedestrian alternate progression is between 62 seconds and 94 seconds.

- **Simultaneous Signal Progression**

Streets with very closely spaced signals or carrying high-speed vehicles are conducive to receiving the maximum benefit from this type of progression. The factors under consideration are the number of signals involved in the signal coordination plan, block lengths and vehicle speeds. Figure 2-3 is an illustration of this technique. It reveals modal trajectories favorable to progression through bandwidth optimization. The bandwidth available depends primarily on the number of signals involved in the signal coordination plan, as can be observed from Figure 2-3.

For a one-way street with four coordinated signals and 50:50 splits, travel speeds at which vehicles could benefit from the technique may be determined from the following equation:

$$1.466 * S_A = L / (C/4)$$

$$S_A = (4*L) / (C*1.466)$$

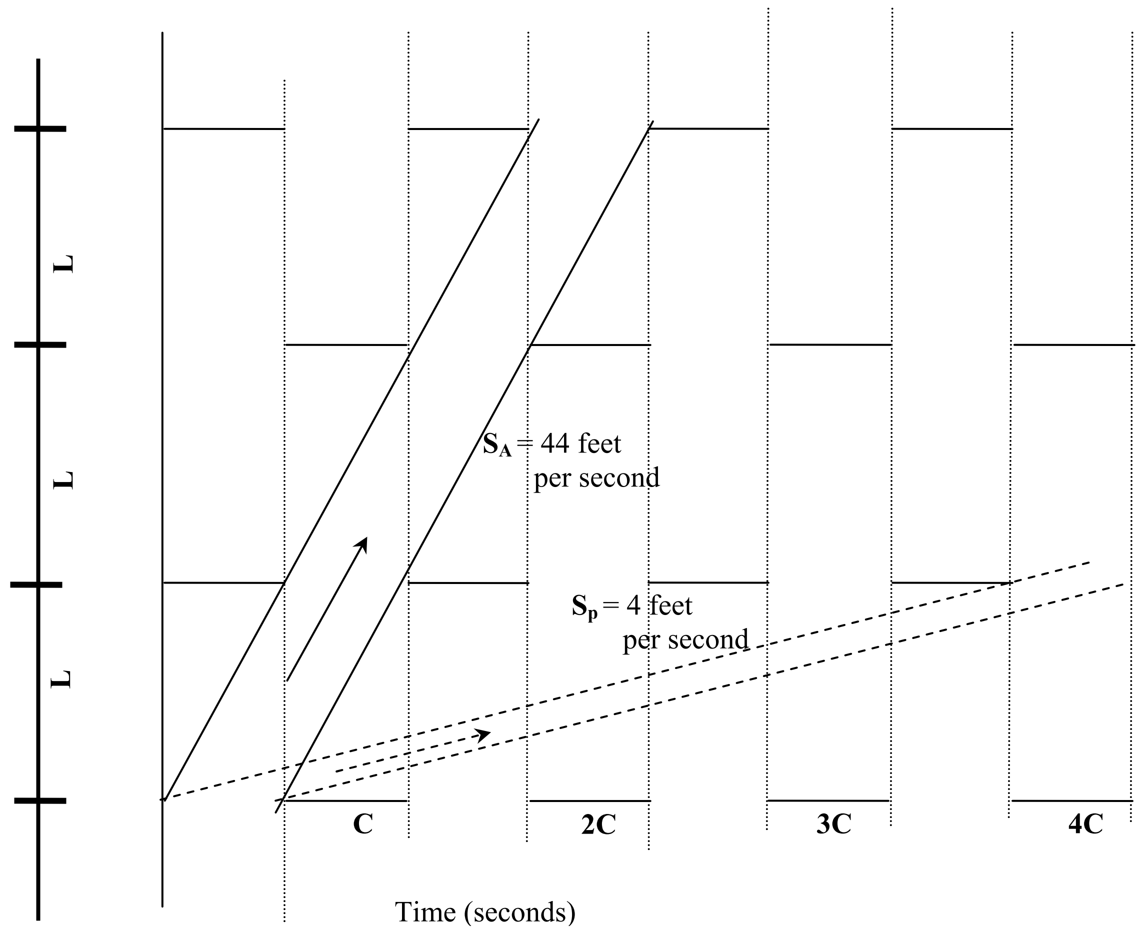
All the terms are as described earlier. So, given that L = 600 feet, S = 30 miles per hour, then the cycle length favorable for simultaneous progression is 55 seconds. These estimates may vary with the number of signals considered for progression. Pedestrians could gain the benefits of progression from the technique if their speed was as below:

$$S_P = L / (2*C)$$

$$C = L / (2* S_P)$$

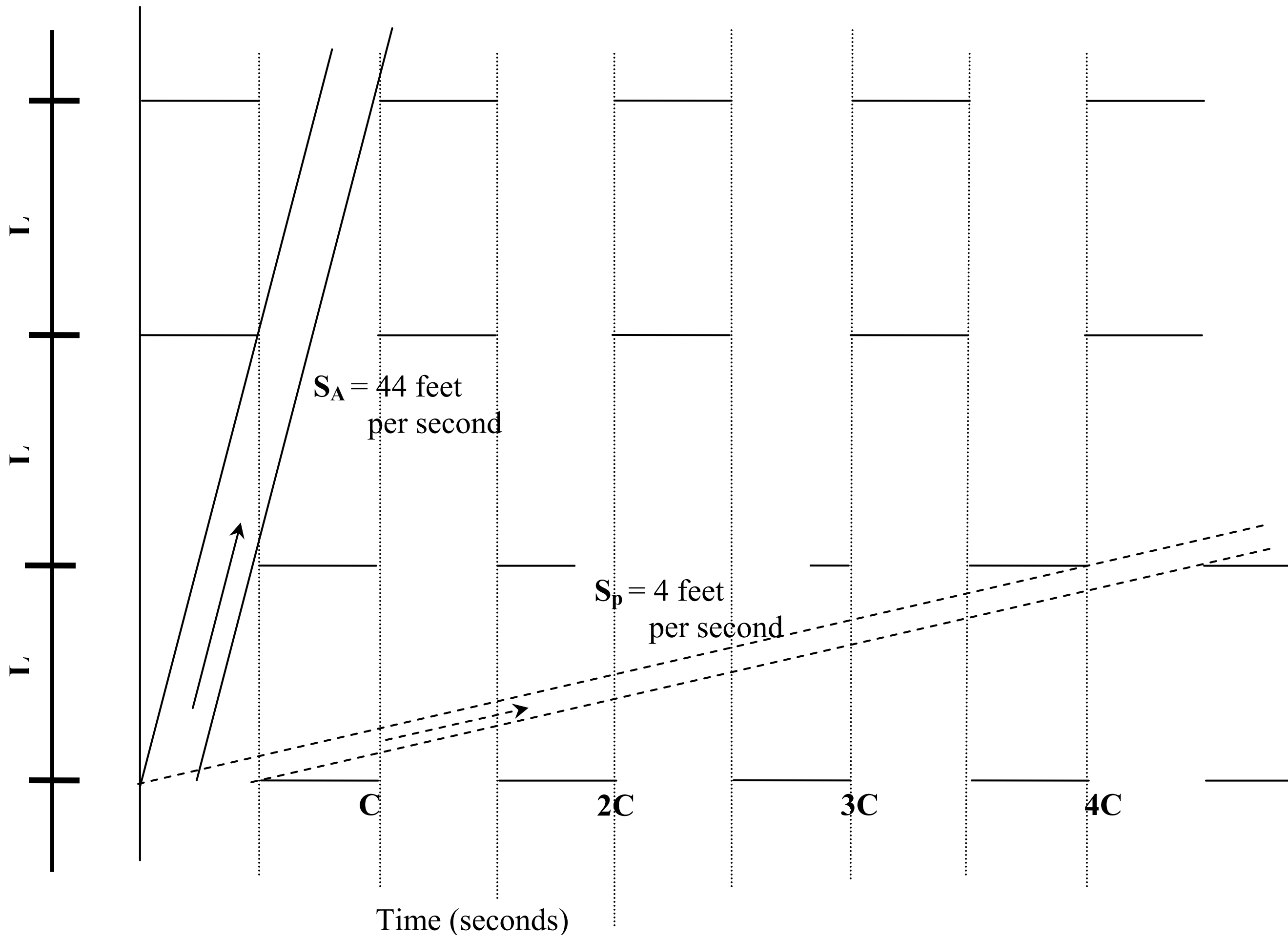
For pedestrians walking at a speed of 4 feet per second on a block length of 600 feet, a suitable cycle length would be 75 seconds.

Figure 2-4 describes the trajectories for pedestrians and vehicles in terms of alternate progression on a two-way street. With the help of these equations and time-space diagrams, cycle lengths and offsets suitable for progression may be determined as in the examples above. These techniques may serve as tools for the engineer to develop a plan to synchronize signals for the progression of both vehicles and pedestrians. The benefit of a signal progression design can be gained if the design progression speed is maintained. Platooning of traffic is more likely to favor uniformity of speeds. The majority of commuters using the route would learn to take advantage of a progression design, according to Mahmassani et al. (2000). Studies have shown that travelers adapt their speeds as they learn the signal coordination pattern due to recurring travel.



C = Cycle length (at each node)
$\mathbf{S_a}$: Automobile speed on arterial
$\mathbf{S_p}$: Pedestrian speed on arterial
L = Block length

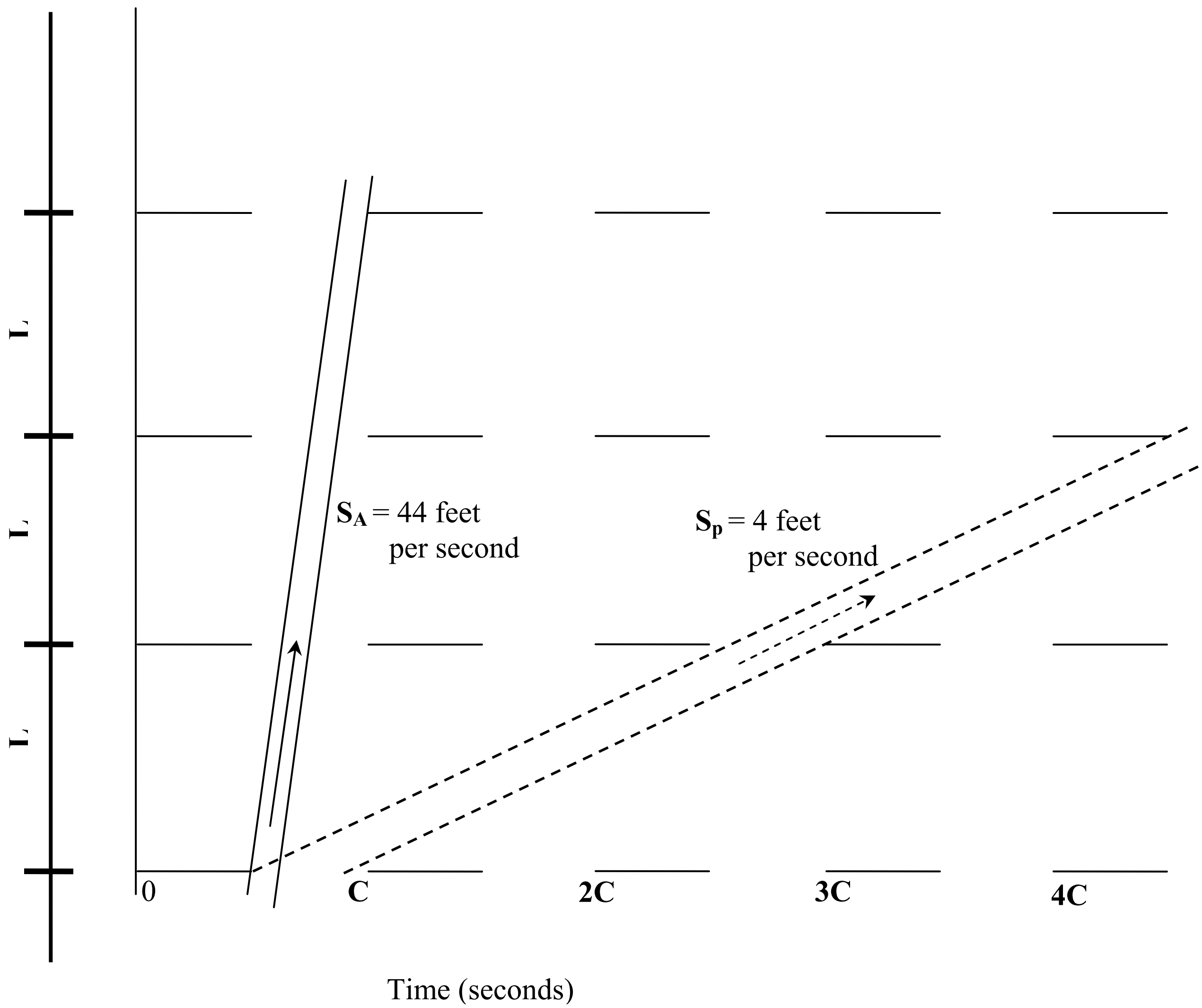
FIGURE 2-1: An example to show one-way alternate progression



C = Cycle length (at each node)

S_a : Automobile speed on arterial **L = Block length**
S_p : Pedestrian speed on arterial

FIGURE 2-2: **An example to show one-way double alternate progression**



Cycle time = 60 seconds (at each node)

S_a : Automobile speed on arterial
S_p : Pedestrian speed on arterial

FIGURE 2-3: **An example to show one-way simultaneous progression**

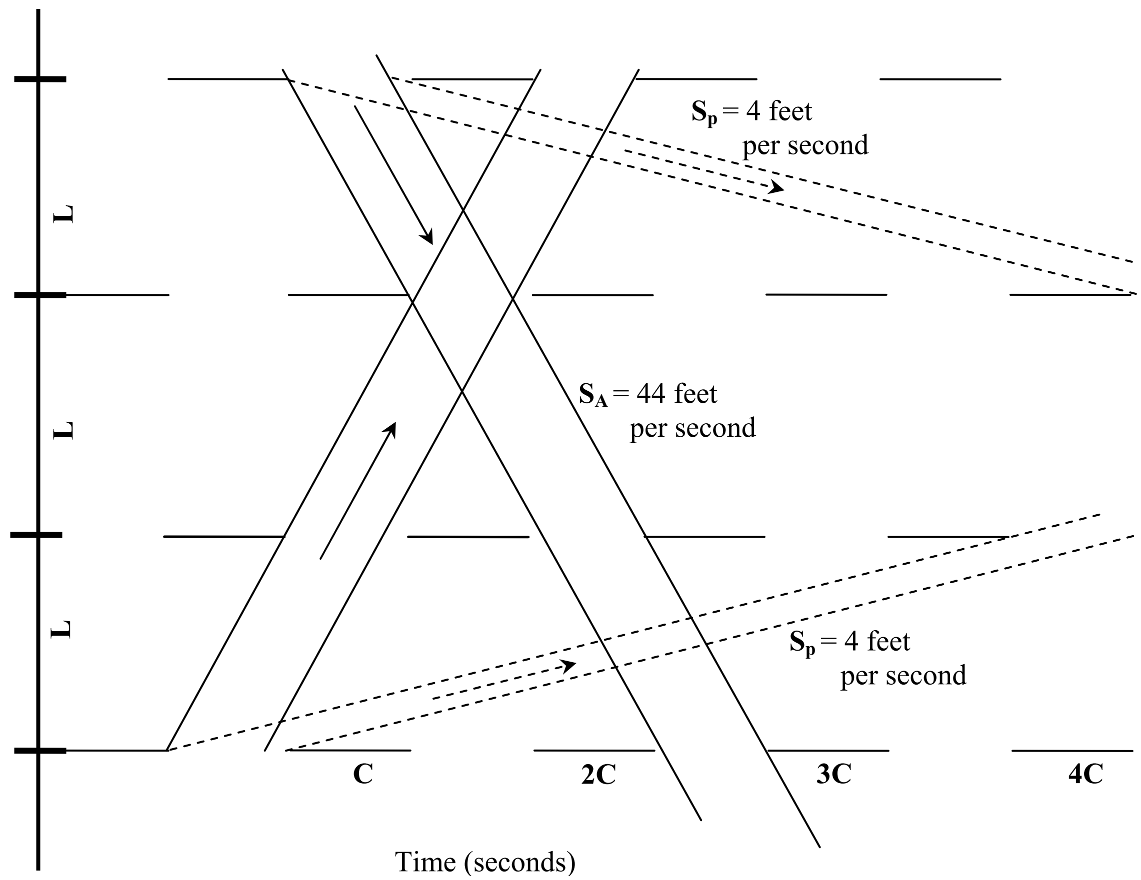


FIGURE 2-4: An example to illustrate two-way alternate progression

2.1.1 Vehicles

The quality of progression has a major impact on the approach delay at signalized intersections. Vehicle progression depends on several factors, such as platooning, bandwidth and offset, roadway capacity, roadside frictions and variability in speeds. According to the Highway Capacity Manual (HCM) 2000, ensuring good progression is a useful technique to control approach delay. The quality of progression is described in terms of the arrival type for the dominant arrival flow for each lane group. Arrivals are not random when there is vehicle platooning in a network. The standard equation used in the HCM in such situations modifies the delay expected with random arrivals by applying an adjustment factor based on the arrival type. According to the HCM 2000 methodology, the average control delay per vehicle for a given lane group is given by

$$d = d_1 * PF + d_2 + d_3 \quad [2.0]$$

where

d = control delay (s/veh)

d_1 = uniform delay (s/veh)

d_2 = incremental delay (s/veh)

d_3 = residual delay (s/veh), which accounts for initial queues due to oversaturation at the start of analysis period

PF = delay adjustment factor for quality of progression

Arrival types that define progression, according to the HCM, are classified as shown as follows:

Arrival Type 1: Typically, a dense platoon, containing over 80% of the lane group of the lane group volume, arrives at the start of the red phase. This type of arrival indicates very poor progression along the link as a result of overall network signal optimization.

Arrival Type 2: This represents the arrival of a moderately dense platoon in the middle of the red phase or dispersed platoon, containing 40% to 80% of the lane group volume, arriving throughout the red phase. This arrival type denotes unfavorable progression on two-way streets.

Arrival Type 3: This comprises random arrivals in which the main platoon contains less than 40% of the approach volume. This arrival type is characteristic of operations at isolated and non-interconnected signalized intersections with maximum dispersion of the platoon among all the arrival types. It may also be used to represent flow along signalized corridors with minimal benefit of progression.

Arrival Type 4: This type refers to the arrival of a moderately dense platoon in the middle of a green phase or a dispersed platoon containing 40 to 80 per cent of vehicles, and represents favorable progression on a two-way arterial.

Arrival Type 5: This represents an arrival pattern where the main platoon arriving at the start of the green phase comprises more than 80 percent of the approach volume. It indicates highly favorable progression for routes carrying high through traffic.

Arrival Type 6: This type of arrival corresponds to exceptional progression where there is high through traffic flow along short block lengths with insignificant side street flow.

The arrival types are associated with delay adjustment factors, also known as progression adjustment factors (PF), and used for determination of approach delay in the

HCM method. The delay adjustment factors in Table 2-1 are calculated based on assumptions that there is no delay for arrivals on green and the flow during the red phase is uniform. The PF from Table 2-1 represents the fraction of uniform delay to be expected with progression compared to the uniform delay if arrivals were random.

TABLE 2-1: **Progression adjustment factors (PF) in Exhibit 16-12 of HCM 2000**

Green Ratio (g/C)	AT-1	AT-2	AT-3	AT-4	AT-5	AT-6
0.2	1.167	1.007	1.000	1.000	0.833	0.75
0.3	1.286	1.063	1.000	0.986	0.714	0.571
0.4	1.445	1.136	1.000	0.895	0.556	0.333
0.5	1.667	1.24	1.000	0.767	0.333	0.000
0.6	2.000	1.395	1.000	0.576	0.000	0.000
0.7	2.556	1.653	1.000	0.256	0.000	0.000

2.1.1.1 Undersaturated versus Oversaturated Flow Conditions

It is a general belief that the benefits of progression become minimal when the arrival volume exceeds the roadway capacity. A well-known theory is that oversaturated traffic conditions are fundamentally different from undersaturated traffic conditions, where progression is achieved through maximization of bandwidth efficiency or optimization of some objective function. If this is true, then there is little reason to provide progression for motor vehicles on congested arterials. To test this belief, an arterial network was modeled using the signal optimization software Synchro. The signal cycle lengths of the intersections within the study area were similar and the green times for the vehicles remained unchanged for this particular study. The block lengths were short as in many central business districts. Delays corresponding to various offset combinations were obtained from the analysis. An overview of the set-up is illustrated in Figure 2-5. The delay ratio is the ratio of the delay for the best offset to the average delay for all the offsets. The analysis was based on the premise that variation in delay ratio with change in volume to capacity ratio would indicate the quality of progression. The best offset refers to the offset corresponding to the minimum delay among all the offset combinations considered. Since cycle length was 60 seconds and offsets were in increments of 5 seconds, there were 12 possible offsets. Vehicular progression patterns were identified from the results of the analysis. Details of the procedure including a description of input data and model output are provided in Appendix B.

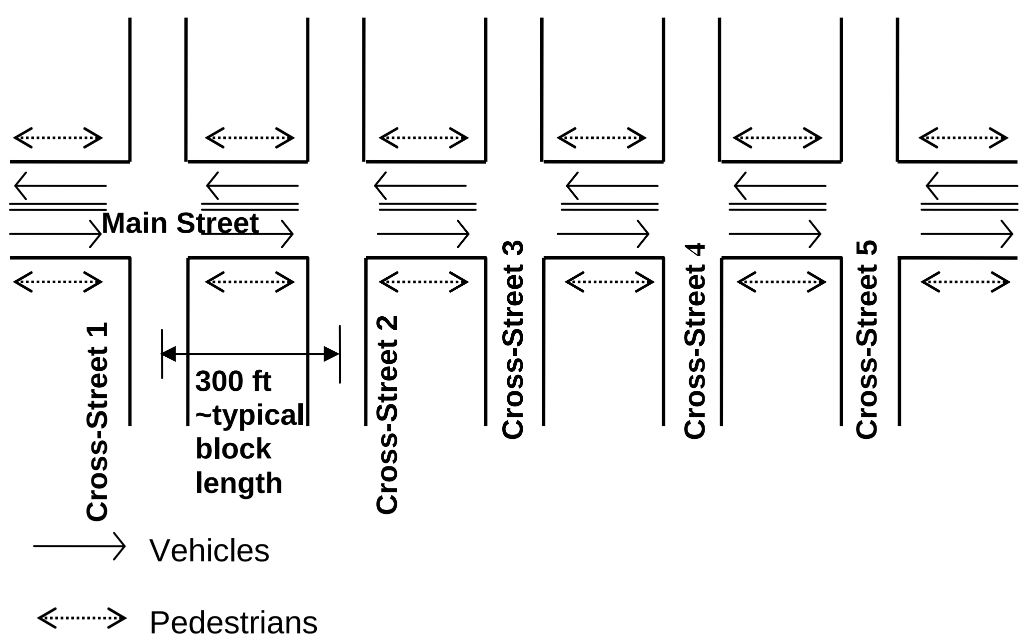


FIGURE 2-5: **Field set-up to study arterial progression**

Figure 2-6 illustrates the progression pattern for vehicles along a pedestrian signalized route. Data points were plotted using the delay results from the model analysis. The graph in Figure 2-6 shows delay ratio as the ordinate and volume to capacity ratio as the abscissa. The delay ratio, as explained previously, is the ratio of the minimum delay among all offsets to the average delay for all offsets. For a fixed roadway capacity and a constant green to cycle length ratio of 0.55, the delay ratio shows significant changes when the demand is below capacity (volume to capacity ratio below 1.0) and then shows little or no change as it approaches unity. As the demand volume increases, there is a corresponding increase in the delay ratio. This indicates that the advantages of providing signal coordination to vehicles abate when the volume to capacity ratio nears unity. As the demand approaches capacity, there is lesser variation in the delay ratio. The curve in Figure 2-5 tends to reach a flat peak when the demand exceeds capacity implying that the delay corresponding to the best offset and average delay for all the offsets become nearly equal. This indicates that the benefits of progression through signal coordination for vehicles become minimal during oversaturated conditions.

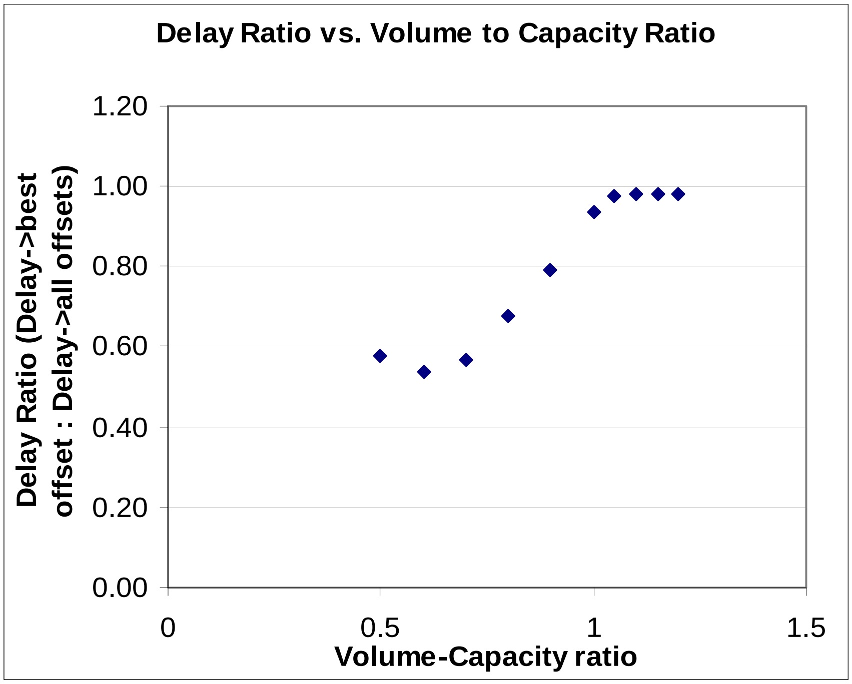


FIGURE 2-6: **Characteristics of vehicle progression with increase in demand**

The delay ratios illustrated in Figure 2-6 correspond to delay adjustment factors described in HCM 2000. The benefits of progression increase with heightening congestion until the network reaches saturation. When the volume to capacity ratio is unity or greater, the benefits become minimal. The figure supports the premise that motor vehicles receive few, if any, benefits from progression when demand is at or over capacity. Therefore, it appears that focusing attention on pedestrian progression rather than motor vehicle progression might be appropriate when motor vehicle congestion is present.

In their paradigm research on signal coordination in oversaturated conditions, Benekohal et al. (2000) stated that "under certain flow and geometric conditions, the quality of signal coordination as measured by the offsets must be accounted for in the capacity estimates". Potential capacity of an approach could remain underutilized if the signals were not properly coordinated. During oversaturated conditions, for short links, there is significant interaction of the downstream queue with traffic departing from the upstream signal. The author stresses that this interaction should be taken into account in order to properly estimate arterial capacity. The research incorporates the effects of signal coordination in the determination of intersection capacity. Opportunities for providing signal coordination in oversaturated conditions are explored.

2.1.2 Pedestrians

Walking, as a mode of transportation, needs to be given due consideration in all relevant transportation network design. Pedestrian progression, similar to vehicle progression, is dependent on several factors including pedestrian platooning patterns and variability in speeds. Mahmassani and Taylor (2000) conducted seminal research in the realm of signal coordination for non-motorized transportation. The research devised techniques to coordinate traffic signals for bicycle progression. Principal considerations for bicycle progression were described in detail with solutions for better bicycle progression. A similar attempt is made by this research in considering the necessary factors for pedestrian progression.

2.1.2.1 Pedestrian speed variability

Virkler (1998) found that the pedestrian speed distribution in one downtown area was bell-shaped with a mean of 1.5 m/s (3.5 mph) and a standard deviation of .278 m/s. HCM 2000 assumes a capacity limitation of 25 persons per minute per foot given that a pedestrian sidewalk of sufficient width (5 ft) is provided.

Another aspect of pedestrian speed variability is the maintenance of the specified average speed between intersections. Yet for short links, the pedestrian can be assumed to be walking at a steady speed for the purpose of signal timing and design. Another factor that affects speed is the grade or slope of the roadway. Grades exceeding 10 percent have a significant effect on pedestrian speeds, according to a FHWA-sponsored technical report prepared by Rouphail et al. (1998).

2.1.2.2 Platooning

Pedestrian progression can be considered in tandem with vehicle progression. In the past, pedestrian arrivals were assumed to be either uniform or random. This perception changed with the passage of time as paradigm research in the area established that there could be significant platooning of pedestrians along key signalized pedestrian routes. A significant contribution to this domain is from a field study conducted by Virkler (1998) near the city center of Brisbane, Australia. The author reports major findings that form the foundation for this current body of research. Data collected from studies conducted on ten Brisbane intersections identified significant benefits of reducing delay through consideration of pedestrian progression. There was an upstream signal to each approach from which the majority of pedestrians moved towards the approach. The number of pedestrians reaching the downstream signal was counted in five-second intervals for a period of approximately fifteen minutes. The signals in the network were operating on fixed cycle lengths ranging from 60 to 90 seconds. Cyclic flow profiles were drawn based on these arrival counts. Figure 2-7 is a cyclic flow profile obtained from one dataset with an upstream signal cycle of 60 seconds. It is also possible to estimate the approach delay at the downstream intersection due to the offset with respect to the upstream signal cycle, from the pedestrian arrival counts. Consequently, delay patterns were obtained by the author, and pedestrian delay adjustment factors were compiled from the field study. The author concludes that the presence of significant pedestrian platooning could boost progression by facilitating the determination of an optimal signal coordination plan. The results can be used to adjust delays based upon random arrivals. Pedestrian delay adjustment factors are compiled to serve as a guide to understanding potential progression benefits. The results also suggest some techniques to determine appropriate signal offsets favorable to pedestrians. One of these techniques involves identification of the flow pattern within the cycle to determine the delay to be expected from any offset. The technique is helpful in optimizing pedestrian and vehicular delay and its application is shown in Section 3.3. This research utilizes the pedestrian delay adjustment factors and applies the technique described in the above research. In another study, the same author found that the effect of signal coordination on average pedestrian delay (based on random arrivals) was prominent at the arterial level.

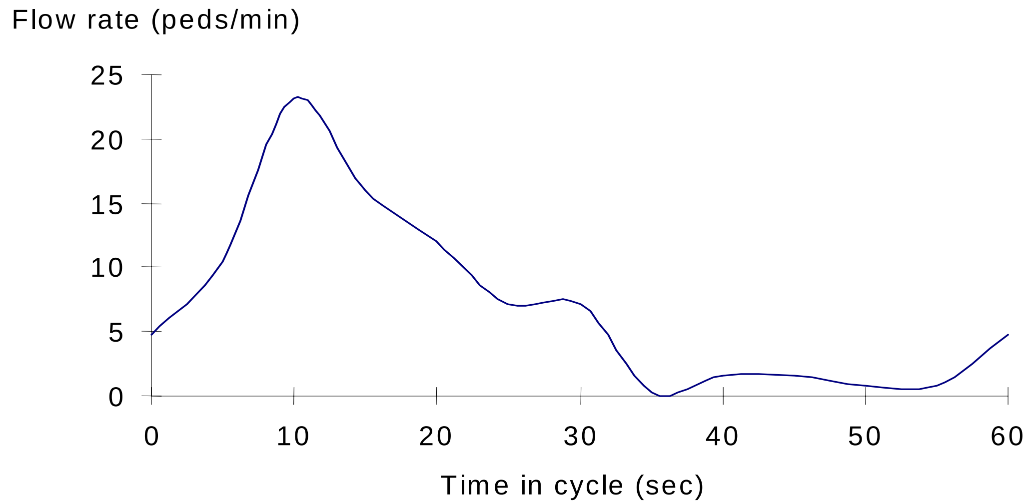


FIGURE 2-7: Flow rate at downstream signal approach versus time in upstream signal cycle

Chilukuri and Virkler (2003) conducted a field study on pedestrian progression with a desire to verify the same results for US roadways. Their study added support to the previous assertions that pedestrian progression should be given due consideration while planning and designing a signal coordination system for an arterial network.

2.2 Network Modeling

The traffic modeling software chosen for demonstration of the method resulted from a thorough study of Chapter 31 of the HCM. According to the HCM, each software model, depending on the application, has its own strengths and weaknesses. Therefore, relevant model features should be linked to needs of an analysis and the model that best satisfies these needs should be selected. The criteria considered paramount in the selection of a model are model capabilities, data availability, ease of use, required resources, model applications and past performance, and validation and calibration.

Based on these criteria, the case study in the research utilizes the software Synchro Version 3.2 to investigate vehicle progression and delay patterns. According to a recent study by Flannery et al. (TRB Annual Meeting 2004) on the use of advanced modeling tools, 70% of those surveyed turned to Synchro when seeking advanced modeling techniques. Their reason was that Synchro provided a more user-friendly environment and its simplicity made it suitable for comparing alternatives. CORSIM and VISSIM were viewed as useful for complicated intersections. Synchro 3.2 was acknowledged as a widely-used windows-based traffic signal timing program with modeling and optimization capabilities. The key features of the program include capacity analysis, coordination, actuated signal modeling, and time-space diagrams.

Synchro employs the Percentile Delay method to model signal coordination and flows near or over capacity. Traffic arrivals are based on a Poisson distribution of the user- input hourly vehicle volumes for each approach. The randomness of vehicle arrivals are accounted for in the estimation of delays. The average delay per vehicle is determined by calculating the delay for five volume scenarios, namely the 10^{th}, 30^{th}, 50^{th}, 70^{th} and 90^{th} percentile volumes. The delays shown in the Travel Time Reports are the sum of vehicle delays for one hour. Synchro 3.2 calculates average (50th) and 95th percentile queue lengths and indicates queue spillback. The 50th percentile queue length is the maximum back of queue length for a cycle with average arrivals. The 95th percentile queue length is adjusted using a Poisson distribution.

2.3 Travel Time Costs and Relative Values of Travel Time

Travel time costs play a major role in the selection of transportation network improvement projects. Costs may be external or internal based on the context of evaluation. Costs borne while traveling on the network are internal costs whereas costs due to environmental impacts of traffic congestion are external costs. The valuation of travel time savings has been a subject of long-standing research. Delay optimization is a monetized benefit to a traveler using the transportation network. Travel time savings constitute a certain benefit to society. Thus, this research aims to optimize delay with a focus on reducing the total user costs of the network. The users in this respect are the travelers using different modes to traverse the network. Comparison of pedestrian and vehicular delay from a socio-economic perspective is important for relative valuation of delays and computation of user costs. According to Hensher (1995), travel time savings studies with a social cost-benefit approach (SCBA) have been applied in evaluating transportation improvements, but with a primarily single-modal focus. SCBA is being actively promoted by economists today as they argue that the benefit items which are quantified and monetized tend to dominate in the ranking and ultimate selection of projects. This paper is an attempt to quantify the benefits of progression through the determination of an optimal signal coordination plan.

Until recently, there was no significant research on the design or investigation of a signal timing plan to optimize travel time delays to both vehicles and pedestrians along a signalized corridor. Considering that vehicle traffic and pedestrians may conflict with each other and cause delay, Noland (1996) says that optimal signal timings should be based on minimizing total delay to both pedestrians and motor vehicles. The author reasons that to estimate the trade-offs of pedestrian delay with motor vehicle delay, it is necessary to consider the relative value of time of each mode. A model is developed that reflects an optimal situation based on relative valuation of travel time for the two modes. Optimal signalization cycles for various ratios of pedestrian-to-vehicular volumes are derived by assuming different relative values of travel time. The limitations to the analysis include the assumption of single-occupant vehicles, and discounting freight travel and other commercial travel associated with higher travel time costs. It is important to quantify the benefits of the trade-off through consideration of the optimal cost.

Noland's concept of the optimal (and minimized) total cost is based on the sum of both vehicle and pedestrian total delay. The value of time for a particular mode is assumed to be constant with additive costs. If D is average delay, T is the value of time, and N is the number of people using each mode, then Noland's equation is as follows:

$$\text{Optimal cost} = \text{minimum } (D_p T_p N_p + D_a T_a N_a) \ldots\ldots\ldots\ldots \quad [2.1]$$

where subscript 'a' indicates automobiles and 'p' indicates pedestrians.

Considerable work has been done in the field of travel time valuation. For automobiles, the AASHTO Manual of User Benefit Analysis of Highway and Bus Transit Improvements (1977) is a reliable source for estimation of the value of time (VOT) and henceforth the research will refer to this as the AASHTO Manual. In the AASHTO Manual, VOT is described as a function of average hourly family income. However, the temporal changes in the economic and social conditions have to be accounted for and can easily be done using data and logistics from federal research organizations, for example, the Bureau of Labor Statistics. Small (1992) suggests on the basis of empirical studies that walking and waiting time could be valued as twice or thrice the value of in-vehicle time. Various studies to estimate the value of time for different modes of transport have found that pedestrian costs are higher than those for other modes, according to Noland (2003). In their NCHRP report, Small et al. (1999) describe how travel time is valued higher under congested conditions by various studies. Accordingly, value of time during peak hours could be higher than the off peak value. This indicates that travel time savings during peak hours can substantially reduce or optimize the user costs of the network. Proper signal coordination in the network could facilitate the optimization of user costs.

2.4 Transportation Modal Patterns

Federal and state efforts to boost pedestrian movement as a vital mode of transportation in urban areas have grown markedly over the past decade. The Intermodal Surface Transportation Efficiency Act (ISTEA) established in 1991 and succeeded by the Transportation Equity Act for the 21st century (TEA-21) contains significant directives for provision of adequate bicycle and pedestrian facilities to create a balanced transportation system. Previously, the federal government favored increased mobility as a means of allowing individuals to participate in a wider range of activities and promoting healthy economic growth. However, this mobility has typically been provided by private motorized transport, which has associated problems such as air pollution, fuel consumption, noise, congestion and driver stress. Therefore, according to Clark and Page

(2000), authorities are investigating options to maintain or enhance individuals' mobility without reliance on private motorized forms of transport. Well-developed transit systems, pedestrian facilities such as marked sidewalks and well-designed federal policies have paved the way for the design of a transportation system that provides economic benefits to all modes of transportation. The Federal Highway Administration's proposal for reauthorization of TEA-21, cited as the Safe, Accountable, Flexible, and Efficient Transportation Equity Act of 2003 (SAFETEA), indicates sufficient federal funds allocated towards relevant bicycle and pedestrian safety projects. The proposed federal Safe, Accountable, Flexible, and Efficient Transportation Equity Act of 2003 (SAFETEA) contains guidelines for funding of pedestrian and bicycle projects. Pedestrian facilities and safety are being actively promoted at the state and federal level. The proposed 2003 federal SAFETEA, in addition to its predecessor Transportation Equity Act for the 21st Century Section (TEA-21), specifically underlines the need "to identify, develop and evaluate strategies to improve energy efficiency and reduce greenhouse gas emissions from transportation sources", (Section 1612 on Transportation, Energy and Environment). Multimodal and intermodal perspectives and sustainable-development oriented design are keywords in transportation planning and design today.

CHAPTER 3

DEVELOPMENT OF METHODOLOGY FOR OPTIMIZATION OF PEDESTRIAN AND VEHICULAR DELAY

In this chapter, a methodology is developed to optimize both pedestrian and vehicular delay by a signal coordination plan. The methodology demonstrated is a tool to devise a signal coordination plan that would provide the benefits of progression to both vehicles and pedestrians. Traffic signals can therefore be better coordinated to reduce both vehicle and pedestrian delay. A diagrammatic representation of the methodology is shown in Figure 3-2 to provide an overview.

3.1 Site Selection

According to the HCM 2000, arterial streets are urban roads that carry a significant volume of longer through trips compared to collector streets. Considering that traffic signals are predominant on arterial streets, providing access to adjoining commercial and residential establishments is also an important function of arterials. Roadside development is dense with commercial uses on urban arterial streets. Signalized intersection spacing ranges from as little as 300 feet in downtown areas to as long as two miles, and with vehicle turn volumes at intersections which usually do not exceed 20 percent of the total traffic approach volume, as described by McLeod (2002). Figure 3-1 provides a glimpse of a pedestrian sidewalk on a typical congested urban street with significant foot traffic. For motor vehicles, downtown streets are more like collectors than arterials. As per HCM 2000, downtown streets are signalized facilities that often resemble arterials. They provide mobility to through traffic and provide access to local businesses. Often, turning movements at downtown intersections are greater than twenty percent of total traffic volume. Downtown streets may function differently with the time of day. Thereby some downtown streets operate like arterials during peak traffic hours.

FIGURE 3-1: Pedestrian movement on a typical urban street

The 2002 National Survey of Pedestrian and Bicyclist Attitudes and Behaviors, jointly sponsored by the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) and the Bureau of Transportation Statistics (BTS), highlights current walkability patterns among the US population. According to the NHTSA and BTS report, among all the walking trips surveyed, 26.9% were less than 0.25 miles. This indicated that more than two-thirds of the walking trips were greater than 0.25 miles. The hypothetical case study demonstrated in Chapter 4 focuses on a stretch of 0.288 miles of a congested urban arterial with significant pedestrian volumes. The 2002 survey report indicates that more than two-thirds of the trip lengths were greater than 0.25 miles. Therefore, it is likely that a significant proportion of pedestrians would traverse the entire length of the arterial stretch under study. This implies that there is potential for platooning of pedestrians along the route. Congestion delay is a major impediment to vehicular traffic progression in urban streets or arterials. A congested urban street is a suitable site to implement this methodology designed to enhance traffic flow. The past few decades have witnessed a steady increase in vehicle volumes and expansion of urban centers. Even during non-congestion periods, travelers may experience excessive delay at traffic signals due to lack of signal coordination. The methodology recommends implementing an optimal signal coordination plan to address such scenarios. Suggested sites where the methodology can be applied most effectively are busy arterial corridors characterized by significant pedestrian activity. Short block lengths would be beneficial to prevent dispersion of pedestrian platoons. Good pedestrian platooning is conducive to a signal coordination plan favorable to pedestrians. Other applicable sites or corridors would be signalized arterials, or pedestrian signalized routes in central business district areas or near universities. According to the US Census Bureau, a central business district (CBD) is an area of very high land valuation characterized by a high concentration of retail businesses, service businesses, offices, theaters, and hotels, and by a very high traffic flow.

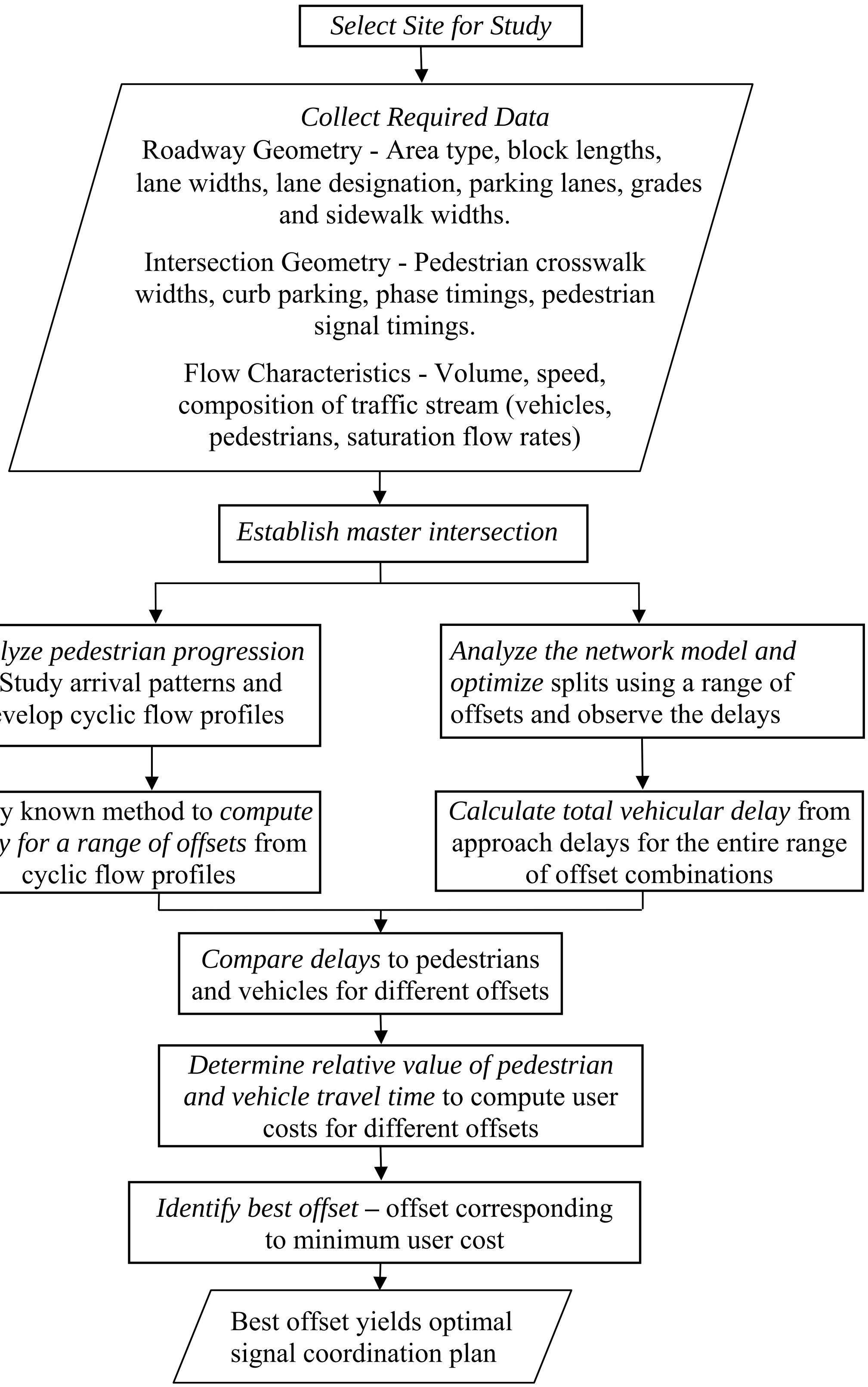


FIGURE 3-2: **Overview of Methodology**

A pre-timed signal control system is normally used for signal coordination. After thorough research, the method described below was developed to recommend a signal timing strategy to effectively control traffic operations and to boost opportunities for progression at such sites.

3.2 Description of Required Data

Data collection for the analysis should be performed with the aim to model field conditions as closely as possible. Conditions that affect motor vehicle and pedestrian progression need investigation in order to identify the needed data. Data collection on field conditions will facilitate calibration of the traffic model. Field data can be used for analyses of pedestrian arrival patterns. The results are dependent on the quality and accuracy of data collection. Nevertheless, a practical approach is required as data collection can be difficult and time-consuming. According to Tarko (2000), corridors with a sequence of signalized intersections are particularly susceptible to internal bottlenecks. Some intersections might be experiencing motor vehicle congestion while carrying high pedestrian flows. Bottlenecks may be formed as the vehicle approach volume nears or exceeds capacity. Therefore, these sites are suitable for data collection. Primary data to be collected include vehicular and pedestrian volumes and signal timings. These data are necessary for the analysis model and are further elucidated in the case study in Chapter 4. The signal optimization software Synchro is utilized to analyze typical congested traffic conditions of the network. Table 3-1 exhibits a list of the data required for the analysis, categorized into roadway geometry, intersection geometry and flow characteristics.

TABLE 3-1: Data required to apply the methodology

Roadway Geometry	**Intersection Geometry**	**Flow Characteristics**
Area type	Pedestrian crosswalk widths	Vehicle and pedestrian volumes
Block length	Curb parking	Speeds
Lane widths	Signal timings for vehicles	Composition of traffic stream
Lane designation	Pedestrian crosswalk widths	Saturation flow rates
Parking lanes	Pedestrian signal timings	Transit or Bus
Grades	Transit stops	Bus blockages
Sidewalk widths	Turning lanes	Mid-block traffic
Driveways	Right turn on red	Peak Hour Factor

3.3 Methods and techniques

At the intersection level, analysis is performed using the techniques described earlier. The following steps are applicable to any intersection in the network excluding the entry/exit nodes. These steps constitute the framework for development of the methodology to find the optimal signal coordination plan.

1. Master intersection

An entry or exit node in the arterial network is established as the master intersection. All offsets during the signal coordination study are set with respect to the phase plan at this intersection.

2. Analysis of pedestrian progression:

Techniques from previous research in the field of pedestrian flow are used to analyze the flow patterns of pedestrians. Traffic signal timings during the peak hour in the network are observed. Pedestrian flow during each five-second time interval is recorded for 15 minutes or the closest period to 15 minutes that is a multiple of the cycle length. Accordingly, an arrival pattern is obtained for each five second interval within the cycle. The purpose of the five-second interval is explained as follows. To optimize delay through signal coordination, infinite possibilities for offset combinations can be considered. For instance, the simple visual techniques in Section 2.1, such as alternate signal progression, double alternate progression, and simultaneous progression can be utilized in feasible situations. However, for practical research purposes, the methodology adopts logical methods to reduce the number of possibilities. Therefore, the arrival pattern in the field studies of previous research is consulted. The technique developed by Virkler (1998) to study the variation in pedestrian delay with change in offset of downstream node with respect to upstream node is adopted. A cyclic flow profile, as described in Section 2.1.2.2 is developed based on arrivals at the downstream signal approach with respect to time in upstream signal cycle. Then, a plot of the approach delay to pedestrians with change in offset of downstream signal with respect to the upstream signal is obtained from the cyclic flow profile. For the purpose of the research, the pedestrian green time and the offsets considered are in multiples of 5 seconds. This explains the purpose of using a five-second time interval during collection of arrival data. Accordingly, a signal cycle of length 60 seconds would yield twelve possible offset combinations ranging from zero to 55 seconds. Approach delay for each combination should be determined. Selecting an appropriate combination of offsets is important since the same combination of offsets will be used for vehicles.

3. Network modeling using signal optimization software

Traffic modeling software is an appropriate tool for traffic experiments where similar field experiments are impractical. Optimized traffic signal timings can be obtained using signal optimization software such as TRANSYT-7F, Synchro or PASSER II. In Synchro, the user can maintain the volume to capacity ratio at a desired level while changing the other input parameters to observe the vehicle delay. Signal optimization aimed at signal coordination is done by Synchro software. The approach delay to vehicles in the route is thus obtained from the modeling of the network on Synchro 3.2. The data collected is entered into the appropriate model input fields and the signal optimization feature is utilized to optimize the splits.

Data required for modeling and optimization of delay is organized into two categories: supply and demand. Supply data include geometric and traffic characteristics of the network. Number of lanes, lane widths, distances between consecutive intersections and the grade for an approach are obtained from suitable sites with high levels of pedestrian and vehicle traffic movement. Demand data primarily includes traffic volumes, comprising through and turn volumes at major intersections throughout the network within the study zone. Based on the supply and demand data, Synchro will generate optimal signal timings for the specified movements. Additional information provided for each link as input for the traffic model include ideal saturated flow, turning speed, protected and permitted right turn and left turn factors, protected and permitted saturated flow rates for the different types of movements. Supplementary demand data regarding parking lanes and maneuvers, peak hour factor, growth factor, heavy vehicles, traffic from mid-block can be specified.

The offsets at consecutive intersections are changed using a pre-determined range of combinations (as explained in Step 2). Accordingly, the delay for various movements will change and the delay values are recorded for each combination. The network performance under each timing plan will depend on various factors, including traffic volumes, signal controller features, and pedestrian activities. Quantitative evaluation of the signal timing and coordination strategy is conducted towards the selection of the optimal plan. Benefits associated with the signal coordination plan are estimated by modeling an arterial stretch comprising five intersections using the Synchro analysis and optimization model. Delay estimates for various signal offsets are converted to a monetary value. Differences between the estimated values reflect the estimated monetary savings or expenditures associated with the signal coordination plans.

4. Comparison of delay

From the approach delays to pedestrians and vehicles at the nodes, the total delay to the respective modes considering the entire network is computed. For the same offset combination, delay to pedestrians is compared with delay to vehicles. The offset causing minimum delay to pedestrians is judged against the offset causing minimum delay to vehicles and based on the observation, possible conclusions are drawn. If they are different, the optimal offset will be determined by assuming a trade-off between the two modes of travel. The purpose is to balance delay costs to vehicles and pedestrians. After in-depth study on the relative valuation of travel time, pedestrian delay can be weighed against vehicle delay without much error. This makes it possible to estimate the cost to any traveler within the network, depending on mode choice. This cost, termed as user cost, is measured in terms of delay. A change in delay will lead to corresponding change in user costs, either savings or expenditures. Benefits can be defined in terms of measures of effectiveness, such as total travel time, delay and stops.

5. Relative valuation of travel time

The perspective on relative values of pedestrian travel time to vehicle travel time varies from agency to agency and from individual and to individual. Some transportation agencies assume that the ratio of pedestrian travel time to vehicle travel time is 1:1 or 2:1 to simplify calculations. This works favorably for most projects. Some agencies might place a higher relative value on the time spent walking. Exposure to weather and greater physical effort required to walk may increase the relative value of pedestrian travel time. A study by Small (1992) supports this assumption by stating that the inconvenience associated with walking and waiting is considered to be double or treble that associated with waiting inside a vehicle. Typically, travelers consider walking or waiting for transit to be as onerous or twice as onerous as traveling in a vehicle. This conclusion is further confirmed in the AASHTO Manual (1997). Sometimes, the agency concerned may need to place a higher value on pedestrian travel time. For instance, in a pedestrian-oriented project such as a transportation facility in an urban center, designers may use higher ratios such as 10:1. Thus, depending on the project and requirements of the evaluation, a reasonable ratio might be chosen by an agency. Once the relative valuation of travel time is known, the user cost or traveler costs can be computed by placing weights on pedestrian delay and the in-vehicle time.

According to NCHRP Report 431, user costs of a facility account for both the physical and economic effects of the performance of the facility on the users. The physical effects are speed and travel time, vehicle operating performance, accident rates and rates of environmental emission. The economic effects relate to the economic value of time and delay, the costs of operating cars and trucks, "economic value" of safety, and the value of clean air. A more detailed analysis would account for all the effects, such as the vehicle operating performance, accident rates and rates of environmental emission. However, this is beyond the scope of this research.

6. Optimization in terms of user costs

To optimize the network performance by signal coordination, it is necessary to observe the effect of various signal coordination plans on travelers by identifying the optimal cost. The optimal cost is obtained from Equation 2.1. It indicates that the efficiency of the network is not compromised. The offset corresponding to the optimal user cost is most likely to form the optimal signal coordination plan.

Improvement in network efficiency will indicate the successful application of the methodology. In the case study that is described in the following chapter, it is assumed that pedestrian travel time is valued twice that of vehicle travel time.

CHAPTER 4

CASE STUDY: AN APPLICATION OF THE METHODOLOGY

A methodology existing in theory should have ample support of its effectiveness before it can be applied to real-world situations. This chapter describes a case study that demonstrates the application of the methodology. The method suggests an inductive approach to the problem by using available data. The chapter is organized under two main headings, the design of the case study and the results of the case study. Section 4.1 describes the site characteristics, procedures and assumptions for the study. It also depicts the field condition for motor vehicle delay analysis on Synchro software. Section 4.2 elaborates on the results of the study and reports the output of various traffic scenarios analyzed by Synchro. Section 4.2 is further subdivided to show the effect of different levels of traffic demand on the network and the impact of considering different relative values of travel time for determination of user costs. The results are discussed separately for the three different traffic situations investigated for the case study. Section 4.3 comprises a discussion on the results with an allusion to past related research. The significance of the observations is elucidated with reference to user costs and benefits. Section 4.4 interprets the results and draws inferences based on known and valid concepts to establish conclusions.

4.1 Design of Case Study

This case study is an application of the methodology described in the previous chapter. The study provides one example of how the method can be applied in the field, in this case, a network spanning a signalized corridor. A methodology is not complete until it is tried and tested in the field. The traffic network, on which the case study is based, may be considered hypothetical, but some data is derived from real-world scenarios and previous research.

4.1.1 Site Characteristics

The major street network has characteristics that could facilitate the effective deployment of a signal coordination plan. The major route is continuous, the network has a grid pattern with route spacing at reasonable intervals, and streets have a generally consistent level of capacity with similar cross-sections. Site characteristics such as these could enhance potential for good progression as a potential benefit of signal coordination. Factors related to favorable progression have already been discussed in Section 2.1 of the research. Previous research involving pedestrian arrival patterns by Virkler (1998) reveals significant potential for favorable progression. Hence, the demonstration will test the hypothetical network using those desirable arrival patterns. The sites where the methodology can be applied most effectively are busy urban signalized corridors characterized by considerable pedestrian movement and significant vehicle traffic volumes during peak traffic conditions. In areas such as in central business districts during certain times of the day, for example, lunch hours, morning or evening commutes, there may be heavy pedestrian traffic. If parking lots are few or far between, or the shops and buildings do not offer parking spaces, walking time for some pedestrians increases. These circumstances may also add to the pedestrian traffic on the street.

The case study assumes a pre-timed signal setting with a separate pedestrian signal at each intersection in the corridor. Traffic signals within the network are operating under similar timings with same cycle lengths.

For analysis of vehicle delay and to obtain desirable progression patterns for vehicles, it can be assumed that there is little or no parking and there are no transit stops along the corridor. All these factors are favorable for good motor vehicle coordination.

4.1.2 Field Set-up on Synchro 3.2

Modeling of motor vehicle delay is required to analyze the effectiveness of the application of the methodology. Synchro software has modeling and optimization capabilites and therefore suitable for the methodology. The field site comprises an urban corridor located in a central business district area. Figure 4-1 below provides a diagrammatic representation of the actual network in the case study.

The arterial stretch under study consists of four short blocks and spans east-west across five signalized intersections. It is on level grade and the slope at each approach is nearly zero. The intersections are equally spaced with pre-timed signals based on the same cycle lengths. The cycle length at the intersections is 60 seconds. The link lengths are short, varying between 346 feet to 350 feet. Lane width is 12 meters for the major street and 15 meters on the side street. There are two shared approach lanes on the major street with no separate turn lanes. The side-street has one travel lane 15 meters wide to carry vehicles in either direction. Pedestrian cross-walks are provided on both the streets with separate pedestrian signals. Figure 4-2 is an illustration of the features of a typical intersection within the network. A traffic network can be created in Synchro by adding street links. Intersections are created using street links. The input data required is entered using the lane window, traffic volume window and timings window and will be described in detail subsequently. The timings window allows data input for signalized intersections. The input parameters include left turn type, phase number, lead/lag assignment, minimum and maximum splits and lost times (clearance and start-up). Synchro calculates the volume to capacity ratios for each lane group.

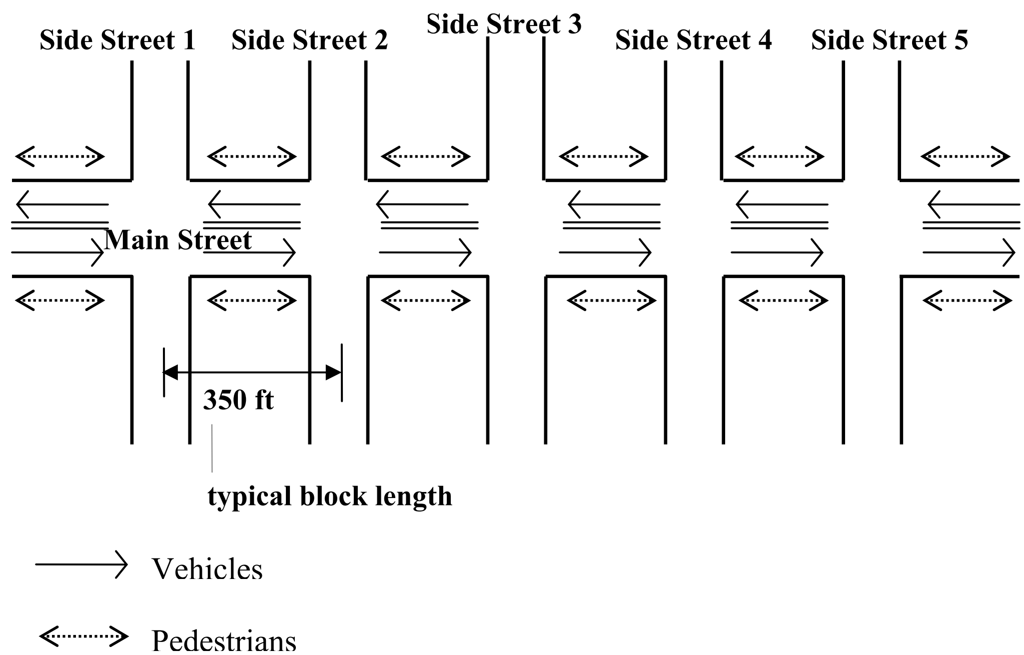


FIGURE 4-1: A view of the study network

Flows and movements within the intersection are depicted in Figure 4-2. Synchro generates various measures of performance for the network such as delay, fuel consumption etc Delay, both total and individual, is the principal performance measure observed and studied.

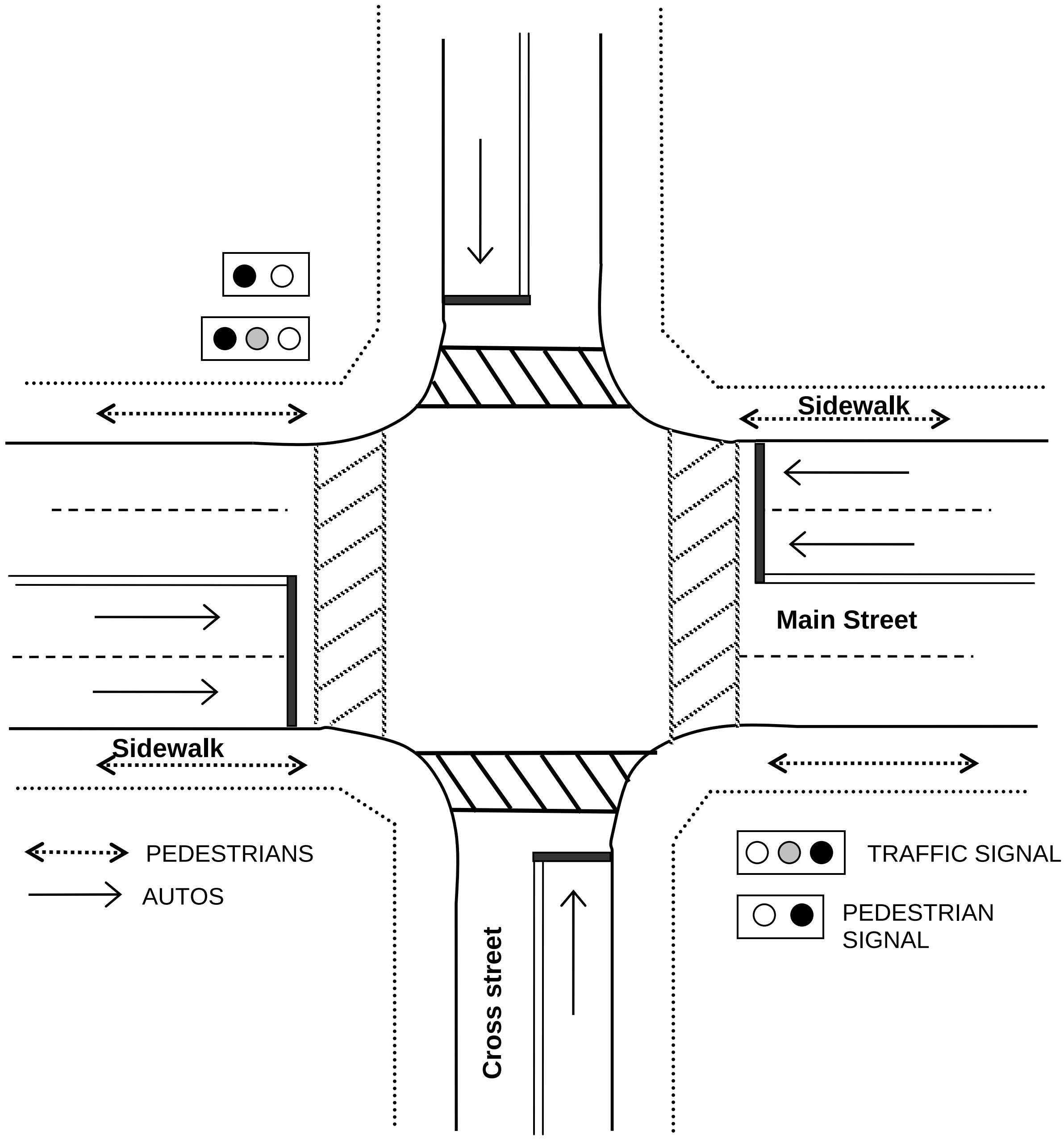


FIGURE 4-2: Flows within a typical intersection in the corridor

Figure A-1 in the Appendix A shows a glimpse of the case study network on Synchro and displays the main street and the side streets. The white circles represent signalized intersections. The first intersection in the primary direction, i.e. east, is selected as the master intersection while setting offsets for the analysis.

Lane data and traffic volumes can be entered through the lane data window and traffic volume input window. The lane data input window, shown in Figure A-2 in the Appendix, allows for input of lane group definitions, lane width, grade, area type, storage length, detector locations, and other applicable information. Lane group definitions affect how traffic is assigned between lane groups. Storage length data are used to determine potential blocking problems.

The volumes input window, shown in Figure A-3 in the Appendix, requires traffic volumes for each movement at an intersection, peak hour factor, growth factor, percent of heavy vehicles, and other related information. Synchro calculates the lane utilization factors and uses these along with the volumes, peak hour factor, and growth factor to calculate the adjusted flow for each movement. On the corridor under consideration, volume of traffic entering and exiting the corridor through the side streets is the same at each intersection. Traffic entering the two-way corridor through the main street is the same in either direction.

4.1.3 Procedures and Assumptions

Procedures:

The traffic model is used to analyze the delay to vehicles and to describe vehicle progression patterns. The following procedure is used for every set of vehicle and pedestrian input volumes.

4.1.3.1 For a given set of pedestrian and vehicle approach volumes, the optimization tool available on Synchro is utilized to maintain a volume to capacity ratio of 1.0 or below at each intersection. The offset at each intersection was changed in increments of 5 seconds, ranging from zero offset to an offset of 55 seconds. This offset combination ranging from zero to 55 seconds is applied between adjacent intersections considering the first intersection along the eastbound direction in the network as the master intersection. For each offset combination, the signal delay to a vehicle approaching an intersection is noted from the traffic model output. Total vehicle delay for the network is computed using the vehicle approach volumes. Table 4-5 shows the network vehicle delay for various offsets. Delays to pedestrians, assuming a pedestrian green time of 15 seconds, are determined according to the procedure developed in previous research using the pedestrian arrival counts made at 5-second intervals within the cycle. The average individual pedestrian delay at each intersection and the corresponding signal offset with respect to the upstream signal cycle are illustrated in Table 4-3. A change in offset would cause variation in the delay to pedestrians based on their arrival within the cycle length of the upstream signal.

4.1.3.2 A thorough review of literature regarding the relative costs or values of travel time was performed to evaluate the user costs to travel on the network. Based on the review, as discussed in Chapters 2 and 3, pedestrian travel time is valued to be twice that of vehicle travel time in urban streets. Monetary values of travel time for vehicles were obtained from the AASHTO Manual (1977). The values were updated using the inflation calculator tool on the Bureau of Labor Statistics website (2003).

Freight and other commercial vehicles that may be associated with a higher value of time than non-commercial vehicles are not considered.

4.1.3.3 The total network delay to both vehicles and pedestrians corresponding to each offset combination is tabulated. User costs are calculated for a given offset combination based on the total network delay.

4.1.3.4 The data is analyzed to find the optimal user cost and to identify the offset associated with the cost. This yields an optimal signal coordination plan for the network.

Assumptions:

Certain assumptions were required in the case study and are discussed accordingly. These assumptions are discussed under two separate headings, assumptions for the model analyses and the other being associated with the basic method. Assumptions related to the basic method are listed below:

- The traffic signals operate at pre-timed settings, at the same cycle lengths and are primarily two-phase signals.
- The intersections are closely and uniformly spaced along the corridor.
- Pedestrians primarily move straight through the corridor, with few turning movements.
- The traffic volumes emulate peak-hour trips in order to design and study the worst-case scenario. However, the signal plan developed by the method can be implemented at peak or off-peak periods depending on congestion level, since it optimizes both pedestrian and vehicular delay.

- Vehicle composition along the arterial can change at every node. Some through vehicles turn right or left and some vehicles turn into the main street to join the through vehicles on the link. Similarly, pedestrians can also turn into the side streets and change their direction of travel. However, there is little impact of signal coordination along the main street on turning pedestrians. Queues on the link on the main street can affect vehicles turning from the side streets and vehicles turning from the main street.
- To simplify the computations, all intersections on the street have identical demand, signal timing, and geometric characteristics.
- The signalized network is on level gradient with no slope at any approach.
- Vehicular volumes are the same in both directions along the main street whereas ninety percent of the pedestrian traffic flow is in one direction and the rest is in the opposite direction.
- Total pedestrian delay for the network is determined by calculating the sum of pedestrian delay for both eastbound and westbound flow.
- Total vehicular delay for the network is calculated by summing up the delay to the main street approach movements at each intersection in the network.
- During motor vehicle congestion, the through vehicular traffic of nearly comprises more than 80 per cent of the traffic approaching the downstream intersection. At peak motor vehicle traffic, through volumes are nearly 1000 vehicles per hour and left and right turn volumes are typically 60 vehicles per hour.
- Due to significant foot traffic, a separate pedestrian signal is extant at each intersection in the corridor.

- Pedestrians proceed only when the 'WALK' signal is on.
- Pedestrian flow remains constant along the corridor, for instance, east-bound pedestrian flow of 1000 pedestrians per hour remains the same from nodes 1 to 5.
- A major proportion (nearly 90%) of pedestrians on the main street travel in the principal direction.
- Pedestrian requirements for safety are addressed. To this end, the minimum green time for both phases must be sufficient to enable pedestrians to cross the street. Computation of the minimum green time to meet pedestrian requirements, as enunciated by McShane, Roess and Prassas (2001), are demonstrated as follows:

Presuming a minimum start-up time of 4 to 7 seconds, minimum time needed by pedestrians to cross the street is:

$$G_p = (4 \leftrightarrow 7) + D_x/S_p \quad [2.1]$$

where: G_p = minimum time needed by a pedestrian to cross the street (sec)

D_x = crossing distance on the street (ft) taken as the distance from the departure curb

to the midpoint of the farthest traffic lane to be crossed

S_p = 15th percentile speed, fps

In the case study demonstrating the methodology presented in Chapter 4, the main street approach has two travel lanes 12 feet wide and the side street approach has one travel lane 15 feet wide. During the main street green, assuming a maximum start-up time of 7 seconds and walking speed of 4 fps, minimum time required to cross the side street:

$$G_{p,\ side} = 7 + D_{side}/4 = 7 + 22.5/4 = 12.62 \text{ seconds} \quad [2.2]$$

During the side street green, minimum time required to cross the main street:

$$G_{p,\ main} = 7 + D_{main}/4 = 7 + 42/4 = 17.5 \text{ seconds} \quad [2.3]$$

It will be observed in the succeeding sections that when the network is analyzed, the minimum green times in the phase timings set by Synchro for the case study satisfy the pedestrian safety requirements.

Assumptions linked to the model analyses are:

- There are very few or almost no transit vehicles on the streets.
- There is no on-street parking along the entire corridor length.
- Though pedestrian signals are present, the signal timing does not incorporate a separate phase for pedestrians.
- The traffic model identifies pedestrian data as the number of pedestrians conflicting with left-turning and right-turning vehicles.
- The peak hour factor (PHF) for all movements is 0.95.
- Default values are accepted for some of the input data requirements regarding geometric and traffic characteristics during the analysis.

4.2 Results of Case Study

Various scenarios were analyzed by varying either vehicle volumes or pedestrian volumes or both in the traffic model. The volume to capacity ratio was observed at each step. For the various scenarios discussed in the results, the volume to capacity ratio for vehicles traveling in a lane on the main street was not allowed to exceed 1.0. This was made possible by adjusting the main street approach volumes. The individual vehicle delay for each offset was recorded from each analysis. Using the approach volumes, relevant delay measures such as network delay and delay ratios were computed. The user cost for each offset was determined from the network delay. The next few paragraphs will be devoted towards the illustration of the results of the model analysis and the pedestrian delay data.

The results obtained from the case study serve as a basis to discuss the background to the research, and also to draw relevant conclusions. A change in the traffic demand volumes in the traffic model affects the volume to capacity ratios and the delay to the approaching traffic. This variation is shown in the plot of Figure 2-5 in Section 2.1.2. An important feature of vehicle progression is thus effectively portrayed through the figure.

4.2.1 Peak period traffic - High through vehicle volumes and high pedestrian volumes

In this section, a peak period traffic situation with high pedestrian volumes (978 vehicles per hour) and high vehicular volumes (1000 pedestrians per hour in the major street) is tested. The data and results are presented in stages in this section so that the methodology becomes clearer. The input volumes for the model analysis are shown in Table 4-1.

Stage 1: Input Data

TABLE 4-1: Vehicle input volumes and pedestrians conflicting with turning movements (peak hour volumes)

		Through	Left turn	Right turn	Conflicting pedestrians
Main Street	**East bound**	**978**	**60**	**60**	**1000**
	West Bound	**978**	**60**	**60**	**1000**
Side Street	**North bound**	**285**	**60**	**60**	**275**
	South bound	**285**	**60**	**60**	**275**

Volume to capacity ratios or v/c ratios:

Volume to capacity ratio for eastbound and westbound vehicles = 0.99

Volume to capacity ratio for northbound and southbound vehicles = 1.00

The optimize intersection splits feature on Synchro was used to optimize the signal timings and to maintain a v/c ratio within 1.0. Table 4-2 shows the individual vehicle delay at each approach for every applied offset combination.

Stage 2: Individual delays

TABLE 4-2: **Individual delay to vehicles with change in offset (from Synchro)**

Offset (sec) Master intersection: Node 1	Signal delay (node 1)		Signal delay (node 2)		Signal delay (node 3)		Signal delay (node 4)		Signal delay (node 5)	
	EB	WB	EB	WB	EB	WB	EB	WB	EB	WB
	(sec/veh)		(sec/veh)		(sec/veh)		(sec/veh)		(sec/veh)	
0	112	108	107	108	107	107	108	107	108	112
2-->5, 3-->10, 4-->15, 5-->20	112	110	105	110	105	111	105	110	105	112
2-->10, 3-->20, 4-->30, 5-->40	112	113	105	113	106	113	106	112	106	112
2-->15, 3-->30, 4-->45, 5-->0	112	115	109	115	109	115	109	115	109	112
2-->20, 3-->40, 4-->0, 5-->20	112	118	112	118	112	118	112	118	112	112
2-->25, 3-->50, 4-->15, 5-->40	112	121	115	121	115	121	115	121	115	112
2-->30, 3-->0, 4-->30, 5-->0	112	119	119	119	119	119	119	119	119	112
2-->35, 3-->10, 4-->45, 5-->20	112	115	121	115	121	115	121	115	121	112
2-->40, 3--20, 4-->0, 5-->40	112	112	118	112	118	112	118	112	118	112
2-->45, 3-->30, 4-->15, 5-->0	112	109	115	109	115	109	115	109	115	112
2-->50, 3-->40, 4-->30, 5-->20	112	106	112	106	113	106	113	105	113	112
2-->55, 3-->50, 4-->45, 5-->40	112	105	110	105	111	105	110	105	110	112

Table 4-2 tabulates the delay per vehicle in seconds as obtained from the traffic model for each approach and each intersection in the network. The eastbound arrivals at node 1 and westbound arrivals at node 5 are random so the delay values do not change with the offsets in Table 4-2. Delay to eastbound vehicles appears to reduce at the downstream nodes for offsets between 5 to 15 seconds. Yet, the percent reduction in delay decreases as offset increases from 5 to 20 seconds. For the westbound vehicles, delay at the internal nodes seems to increase as offset between consecutive nodes along the route changes from 5 to 35 seconds. The signal coordination plan apparently favors progression for offsets between zero and 5 seconds and between 50 and 55 seconds.

TABLE 4-3: Delay to pedestrians with change in offset

Offset between consecutive nodes	Average pedestrian delay on each link (seconds/pedestrian)	
	EB	WB
0 sec	12.92	14.32
5 sec	8.67	8.18
10 sec	7.36	6.36
15 sec	6.78	5.23
20 sec	10.58	8.86
25 sec	14.07	13.18
30 sec	17.87	17.95
35 sec	22.24	22.95
40 sec	26.61	27.95
45 sec	28.81	28.64
50 sec	21.33	28.86
55 sec	10.96	20.00

The delays given in Table 4-3 are based on the information depicted in Figure 2-7. The cyclic flow profile illustrated in the figure was derived by Virkler (1998) and its theory is described in detail in Section 2.1.2.2. The cycle time at each signal in the network is 60 seconds and the main street pedestrian signal has a 'WALK' time of 15 seconds. Accordingly, Table 4-3 shows the average delay to a pedestrian on the arterial as an effect of different offsets between signals. The 'WALK' time specified satisfies the requirement for the minimum pedestrian crossing time. Minimum pedestrian green time required to cross the main street safely is calculated in Equation 2.2 as 12.62 seconds, which is less than the 'WALK' time provided per cycle. The individual vehicle delays for 500 pedestrians per hour on the main street are significantly lower than those given in Table 4-2 for 1000 pedestrians per hour.

Stage 3: Optimized signal timings

TABLE 4-4: Phase splits resulting from modeling on Synchro

	East-bound traffic	**West-bound traffic**	**North-bound traffic**	**South-bound traffic**
Maximum split (s)	37	37	23	23
Minimum split (s)	22	22	22	22
Yellow + all red time (s)	5	5	5	5
Lost time (s)	3	3	3	3

The signal timings generated by Synchro are shown in Table 4-4. The minimum green time for vehicles, as indicated by the minimum split, is 22 seconds for all movements. This complies with the minimum pedestrian green time requirements. Thus the signal splits provide adequate safety to pedestrians. The table shows that the minimum pedestrian approach delay in a link occurs when the offset with respect to the upstream node is 15 seconds.

The delay value shown in Table 4-2 and Table 4-3 is equivalent to the "delay per peak period traveler". An annual study conducted by Texas Transportation Institute (TTI) researchers, Lomax and Schrank (2002) introduced this measure to provide a more appropriate description of the extra time spent traveling when traffic demand on the roadway is at its highest.

Stage 4: Network delay

TABLE 4-5: **Network vehicle delay for each offset combination**

Offset combination (sec)	Network vehicle delay (hour within peak hour)		
	EB	WB	Total
0 sec	165.31	165.31	330.62
5 sec	162.26	168.67	330.93
10 sec	163.18	171.72	334.89
15 sec	167.14	174.46	341.60
20 sec	170.80	178.12	348.92
25 sec	174.46	181.78	356.24
30 sec	179.34	179.34	358.68
35 sec	181.78	174.46	356.24
40 sec	178.12	170.80	348.92
45 sec	174.46	167.14	341.60
50 sec	171.72	163.18	334.89
55 sec	168.67	162.26	330.93
	Delay Ratio:		0.964

The variation in network delay with change in offset between nodes is shown in Table 4-5. It is clear from Table 4-5 that motor vehicles gain little benefit from signal coordination since vehicle delay changes are small for different offsets. The ratio of the minimum delay to the average delay for all offsets tested for the signal coordination plan is termed as delay ratio. The delay ratio obtained by modeling motor vehicle delay is 0.964.

TABLE 4-6: **Network pedestrian delay varies with the offset**

Offset (sec)	**Network pedestrian delay (hour within peak hour)**
0 sec	21.33
5 sec	17.29
10 sec	16.93
15 sec	16.29
20 sec	20.41
25 sec	23.65
30 sec	27.29
35 sec	31.55
40 sec	35.87
45 sec	37.86
50 sec	29.69
55 sec	19.85
Delay Ratio:	0.656

The network pedestrian delay is calculated by summing up the total pedestrian delay on each link in the corridor. Table 4-6 shows that pedestrians in the network experience minimum delay when the offset is 15 seconds. The ratio of the delay for the best offset to the average delay for all offsets is known as delay ratio. The delay ratio for pedestrians, for the given traffic conditions is 0.656.

Table 4-7 illustrates the comparison between pedestrian delay and vehicle delay.

TABLE 4-7: Comparison of network pedestrian delay and vehicle delay

Offset (sec)	Network delay (hour within peak hour)			
	EB vehicles	WB vehicles	Total vehicle delay	Pedestrians
0 sec	165.31	165.31	330.62	21.328
5 sec	162.26	168.67	330.93	17.288
10 sec	163.18	171.72	334.89	16.928
15 sec	167.14	174.46	341.60	16.288
20 sec	170.80	178.12	348.92	20.408
25 sec	174.46	181.78	356.24	23.648
30 sec	179.34	179.34	358.68	27.288
35 sec	181.78	174.46	356.24	31.548
40 sec	178.12	170.80	348.92	35.870
45 sec	174.46	167.14	341.60	37.861
50 sec	171.72	163.18	334.89	29.695
55 sec	168.67	162.26	330.93	19.850

In Table 4-7, the change in pedestrian delay with different offsets is more prominent than the corresponding change in vehicle delay. On observation, the maximum total vehicle delay is greater by approximately 8.5% than the minimum total vehicle delay. However, the maximum total pedestrian delay exceeds twice the minimum total pedestrian delay.

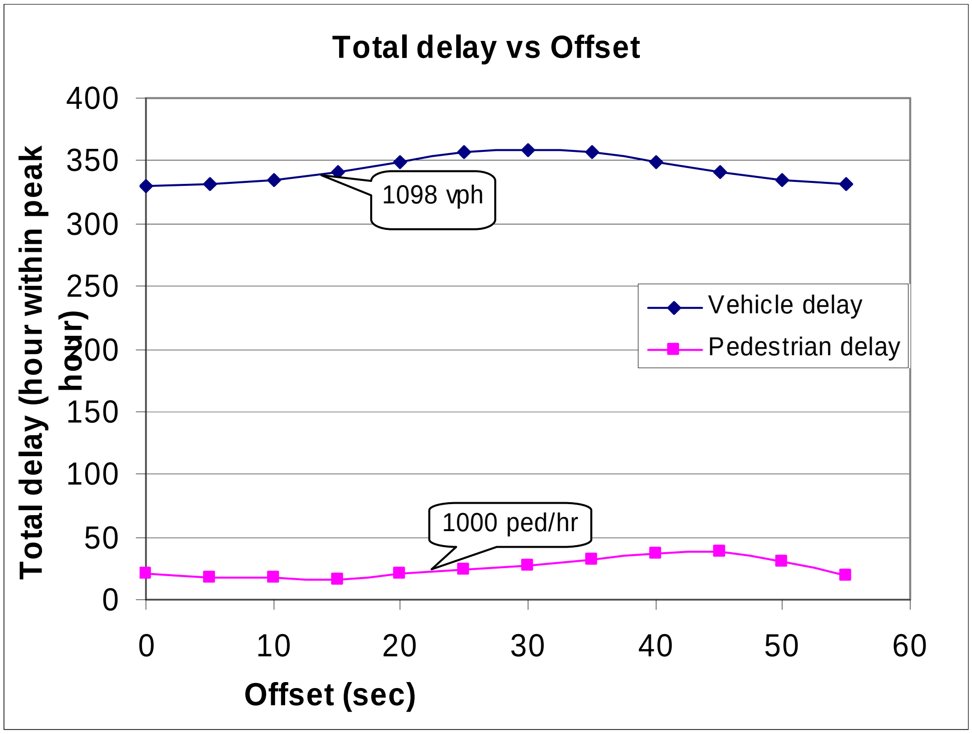


FIGURE 4-3: Network total vehicle delay and pedestrian delay variation with offsets

Figure 4-3 provides a graphical representation of the variation in pedestrian delay and vehicle delay with different signal coordination plans. Figure 4-3 reveals that the best offsets for vehicles and pedestrians are not the same. The best offset for pedestrians is 15 seconds whereas that for vehicles is 0 seconds. Pedestrian delay shows greater variation with change in offset than vehicle delay. The through movement of vehicles and pedestrians are comparable, with 978 vehicles per hour and 1000 pedestrians per hour at each main street approach along the corridor. At this juncture, the delay ratio needs to be taken into consideration. The delay ratio for a particular volume scenario is the ratio of the delay associated with the best offset and the average delay for all offsets. This ratio gives an indication of the nature of traffic progression along the network. The results indicate that the delay ratio for vehicles, is approximately 0.96 and 0.66 for pedestrians. In the Highway Capacity Manual, the progression adjustment factor (PF) to adjust the delay for uniform arrivals is given as 1.0. PF gives an indication of the traffic progression through the network. Previous research by Virkler (1998) has shown that the delay ratios for a particular volume scenario can be considered equivalent to the PF values in the HCM as described in Section 2.1.1. Vehicle volumes are high and there is considerable pedestrian movement in this model scenario. The delay ratio for vehicles is 0.96, about 4% less than the PF for random arrivals (arrival type 3) indicated in HCM. The HCM specifies the PF for favorable progression (arrival type 4) as 0.576 for a g/C ratio of 0.6. The g/C ratio for the traffic condition modeled is 0.61. Thereby, with a delay ratio of 0.66, pedestrians could benefit from the signal coordination plan. It is well-known that random arrivals do not benefit from progression through traffic signal coordination. Since the delay ratio for vehicles in this volume scenario is close to 1.0, it is an indication of unsatisfactory motor vehicle progression. Consequently, vehicle traffic will gain minimal benefits of progression through signal coordination. Hence, if motor vehicle congestion limits the progression of vehicles, opportunities to provide progression to other competing modes such as pedestrians should be explored. It would be logical to provide the benefit of progression to pedestrians through better coordinated signals. In doing so, network efficiency could be attained by optimizing the user costs in the network. The procedure to determine optimal user costs is shown in Table 4-8. This procedure will be used in this research to identify the optimal signal coordination plan for any flow condition.

Stage 6*:* Network user costs

TABLE 4-8: Network user cost determined for high pedestrian volumes

(Pedestrian delay valued as twice the vehicle delay)

Offset	Total delay to vehicles (hr within peak hr), Da	Total delay to peds (hr within peak hr), Dp	Value of vehicle time, T_a $/hr	Value of ped time, T_p ($/hr)	Average auto occupancy	User cost with vehicles and peds ($/hr)	User cost: vehicles only ($/hr)
0 sec	330.62	21.33	1.396	2.792	1.22	622.63	563.09
5 sec	330.92	17.29	1.396	2.792	1.22	611.87	563.60
10 sec	334.89	16.93	1.396	2.792	1.22	617.62	570.36
15 sec	341.6	16.29	1.396	2.792	1.22	627.26	581.79
20 sec	348.92	20.41	1.396	2.792	1.22	651.23	594.25
25 sec	356.24	23.65	1.396	2.792	1.22	672.74	606.72
30 sec	358.68	27.29	1.396	2.792	1.22	687.06	610.88
35 sec	356.24	31.55	1.396	2.792	1.22	694.80	606.72
40 sec	348.92	35.87	1.396	2.792	1.22	694.40	594.25
45 sec	341.6	37.86	1.396	2.792	1.22	687.49	581.79
50 sec	334.89	29.69	1.396	2.792	1.22	653.27	570.36
55 sec	330.92	19.85	1.396	2.792	1.22	619.03	563.60

In Table 4-8 and Figure 4-7, pedestrian travel time is valued twice as that of vehicle travel time based on the literature study described in Section 2.4. Table 4-8 shows the value of vehicle time estimated in dollars per hour within the peak hour. This estimate is obtained from the value of travel time for work trips given in the AASHTO Manual (1977). The average vehicle occupancy is given as 1.22 based on observation of contemporary traffic conditions. This is an important step leading to the evaluation of the total costs to any traveler within the network termed as 'user costs'.

If TD is total delay and T is the value of time, then based on Equation 2.1,

$$\text{User cost} = \{(TD)_p * T_p + (TD)_v * T_v\} \ldots\ldots\ldots\ldots\ldots\ldots \text{[2.4]}$$

where subscript ‘v’ indicates vehicles and ‘p’ indicates pedestrians.

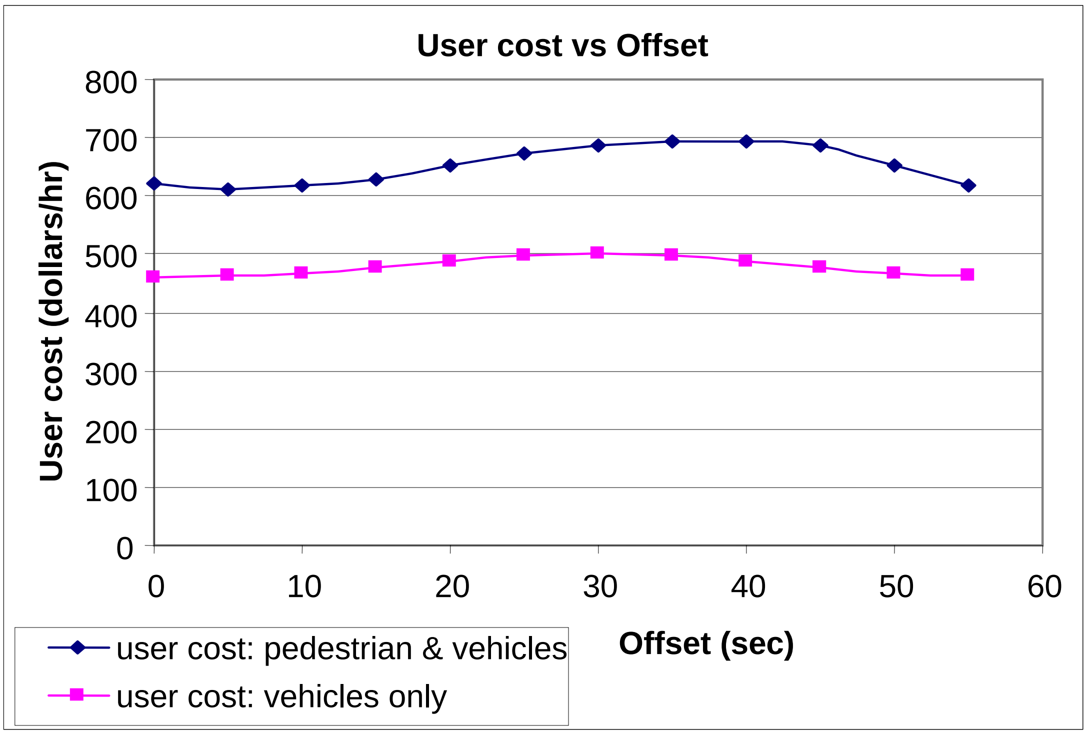


FIGURE 4-4: User cost in the network varies with the offset between nodes

Figure 4-4 has two curves showing user costs. Assuming that consideration of both modes is ideal to signal coordination planning, Figure 4-4 shows the implications of incorporating pedestrian delay in a signal coordination plan. The user cost considering vehicles and pedestrians accounts for delays to both the modes whereas the user cost for vehicles considers only vehicle delay. There is greater variation in user cost when both pedestrians and vehicles are considered than when simply vehicle delay is reckoned with.

This view is supported by comparing the two user cost curves in the figure. User cost savings in terms of the difference between maximum and minimum user costs is 83 dollars per hour during the peak traffic period when both vehicles and pedestrians are considered. The savings reduce to 48 dollars per hour when only vehicles are accounted for. Also the offset associated with the minimum user cost considering both pedestrians and vehicles is different from that considering only vehicles. If pedestrian delay is ignored, the minimum user cost would be for an offset of 0 seconds, as shown in Table 4-8. For this offset, the actual user cost considering the delays to both the modes is 623 dollars. This implies a loss of user savings to the extent of 60 dollars per hour. Moreover, the minimum user cost in the ideal case is nearly 611 dollars. Thus user costs savings to the tune of 12 dollars per hour would be lost. The maximum user cost is 13.6% higher than the minimum user cost in the former case and only 8.5% higher in the latter. A traffic engineer can inadvertently inflict greater user cost on a traveler in the network by not considering the progression of pedestrians.

4.2.2 Effect of change in pedestrian volumes on signal synchronization

In this scenario, a traffic condition with significantly lower pedestrian volumes is analyzed and compared to the pedestrian volumes applied in Section 4.2.1. It is expected that a reasonable comparison of the different situations will provide greater insight into the problem of signal coordination in congested conditions. The comparison is discussed in this section. However, some tables and graphs illustrating the comparison are presented in the Appendix. Table 4-9 shows the total delay and user costs when pedestrian volumes reduce to 500 pedestrians per hour from 1000 pedestrians per hour as given in Section 4.2.1 with other parameters remaining unchanged.

TABLE 4-9: Network user cost considering relative values of travel time

Offset	Total vehicle delay (hr within peak hr), Da	Total pedestrian delay (hr within peak hr), Dp	Value of vehicle time, T_a $/hr	Value of pedestrian time, T_p ($/hr)	Average auto occupancy	User cost for vehicles and peds ($/hr)
0 sec	161.04	10.67	1.396	2.792	1.22	304.08
5 sec	161.04	7.93	1.396	2.792	1.22	296.40
10 sec	165.62	7.09	1.396	2.792	1.22	301.85
15 sec	171.72	6.69	1.396	2.792	1.22	311.12
20 sec	179.95	9.05	1.396	2.792	1.22	331.73
25 sec	188.19	11.25	1.396	2.792	1.22	351.90
30 sec	188.49	13.65	1.396	2.792	1.22	359.12
35 sec	188.19	16.41	1.396	2.792	1.22	366.31
40 sec	179.95	19.13	1.396	2.792	1.22	359.88
45 sec	171.72	20.41	1.396	2.792	1.22	349.43
50 sec	165.62	16.25	1.396	2.792	1.22	327.42
55 sec	161.04	9.93	1.396	2.792	1.22	301.98

The network user cost is computed by valuing vehicle travel time as twice the pedestrian travel time. Table 4-9 reveals that in this scenario, the minimum user cost is 23.6% lower than the maximum user cost. This is significantly different from the previous scenario with greater pedestrian traffic where the difference between the minimum and maximum user costs was 13.55%. The minimum user cost when there is a directional traffic of 1000 pedestrians per hour (in Section 4.2.1) exceeds twice the minimum user cost when the pedestrian traffic per hour is 500. It indicates that there is scope for enhancing progression during high traffic volumes on the main street by coordinating signals.

TABLE 4-10: Vehicle input volumes and pedestrians conflicting with turning movements (peak hour volumes)

		Through	Left turn	Right turn	Conflicting pedestrians
Main Street	**East bound**	**978**	**60**	**60**	**500**
	West Bound	**978**	**60**	**60**	**500**
Side Street	**North bound**	**285**	**60**	**60**	**275**
	South bound	**285**	**60**	**60**	**275**

Table 4-10 shows the volumes input for the analysis. Pedestrian demand has nearly reduced to half the demand compared to the previous section.

TABLE 4-11: **Individual delay to vehicles with change in offset (from Synchro)**

Offset (sec) Master intersection: Node 1	Signal delay (node 1)		Signal delay (node 2)		Signal delay (node 3)		Signal delay (node 4)		Signal delay (node 5)	
	EB	WB	EB	WB	EB	WB	EB	WB	EB	WB
	(sec/vehicle)		(sec/vehicle)		(sec/vehicle)		(sec/vehicle)		(sec/vehicle)	
2→0, 3→0, 4→0, 5→0	57	52	51	52	52	52	52	51	52	57
2→5, 3→10, 4→15, 5→20	57	55	49	54	49	55	49	54	49	57
2→10, 3→20, 4→30, 5→40	57	57	50	57	50	58	50	57	50	57
2→15, 3→30, 4→45, 5→0	57	59	53	59	53	59	53	60	53	57
2→20, 3→40, 4→0, 5→20	57	63	56	63	56	63	56	63	56	57
2→25, 3→50, 4→15, 5→40	57	66	59	66	60	66	60	66	60	57
2→30, 3→0, 4→30, 5→0	57	63	63	63	63	63	63	63	63	57
2→35, 3→10, 4→45, 5→20	57	60	66	60	66	60	66	59	66	57
2→40, 3→20, 4→0, 5→40	57	56	63	56	63	56	63	56	63	57
2→45, 3→30, 4→15, 5→0	57	53	60	53	59	53	59	53	59	57
2→50, 3→40, 4→30, 5→20	57	50	57	50	58	50	57	50	57	57
2→55, 3→50, 4→45, 5→40	57	49	54	49	55	49	54	49	55	57

Table 4-11 illustrates the delay output by Synchro for each approach vehicle in either direction on the main street. The first column lists the offsets at each node in the study arterial route for each analysis run. The offset is assumed to always zero at node 1 or the first node (eastward-bound vehicles) and offsets corresponding to other nodes vary in steps of five to fifty-five seconds. The delays differ between links and between offset combinations. The pedestrian arrival patterns are assumed to be the same as in the scenario in Section 4.2.1.

TABLE 4-12: Phase splits optimized by modeling on Synchro

	East-bound traffic	West-bound traffic	North-bound traffic	South-bound traffic
Maximum split (s)	37	37	23	23
Minimum split (s)	22	22	22	22
Yellow + all red time (s)	5	5	5	5
Lost time (s)	3	3	3	3

The phase splits for each traffic movement and signal timings as optimized by Synchro are depicted in Table 4-12.

TABLE 4-13: Network vehicle delay for various offset combinations

Offset	**Network total vehicle delay (hour within the peak hour)**		
	EB trips	**WB trips**	**Total**
0 sec	80.52	80.52	161.04
5 sec	77.17	83.88	161.04
10 sec	78.39	87.23	165.62
15 sec	82.05	89.67	171.72
20 sec	85.71	94.25	179.95
25 sec	90.28	97.91	188.19
30 sec	94.25	94.25	188.49
35 sec	97.91	90.28	188.19
40 sec	94.25	85.71	179.95
45 sec	89.67	82.05	171.72
50 sec	87.23	78.39	165.62
55 sec	83.88	77.17	161.04
		Delay Ratio	0.93

The delay ratio of 0.93 in Table 4-13 indicates that vehicles stand to gain few, if any, benefits from the signal coordination plan. The reason is that the delay ratio is high, very close to 1.0 which is the PF for random arrivals in the HCM.

TABLE 4-14: Network pedestrian delay for various offset combinations

Offset	Network Total Pedestrian delay (hour within the peak hour)
0 sec	10.675
5 sec	7.926
10 sec	7.086
15 sec	6.686
20 sec	9.046
25 sec	11.246
30 sec	13.646
35 sec	16.406
40 sec	19.126
45 sec	20.406
50 sec	16.246
55 sec	9.926
Delay Ratio:	0.541

Tables 4-13 and 4-14 show that by lowering the pedestrian volumes, the delay ratios for both pedestrians and vehicles become lower than the corresponding values obtained for the situation in Section 4.2.1. However, the delay ratio for pedestrian flow remains considerably lower than that for vehicles. The delay ratio for vehicles, that is, 0.93 is still closer to 1.0 (PF for random arrivals) than that for pedestrians. Signal coordination contribution to traffic progression reduces as the delay ratio approaches one.

TABLE 4-15: Comparison of network total pedestrian delay and vehicle delay

Offset	Network total delay (hour within the peak hour)			
	EB delay	WB delay	Total delay	Pedestrian delay
0 sec	80.52	80.52	161.04	10.675
5 sec	77.17	83.88	161.04	7.926
10 sec	78.39	87.23	165.62	7.086
15 sec	82.05	89.67	171.72	6.686
20 sec	85.71	94.25	179.95	9.046
25 sec	90.28	97.91	188.19	11.246
30 sec	94.25	94.25	188.49	13.646
35 sec	97.91	90.28	188.19	16.406
40 sec	94.25	85.71	179.95	19.126
45 sec	89.67	82.05	171.72	20.406
50 sec	87.23	78.39	165.62	16.246
55 sec	83.88	77.17	161.04	9.926

Table 4-15 shows that there is a wider variation in pedestrian delay than in vehicle delay for different offsets. The changes in vehicle delay for different offsets are not significant compared to the changes in pedestrian delay.

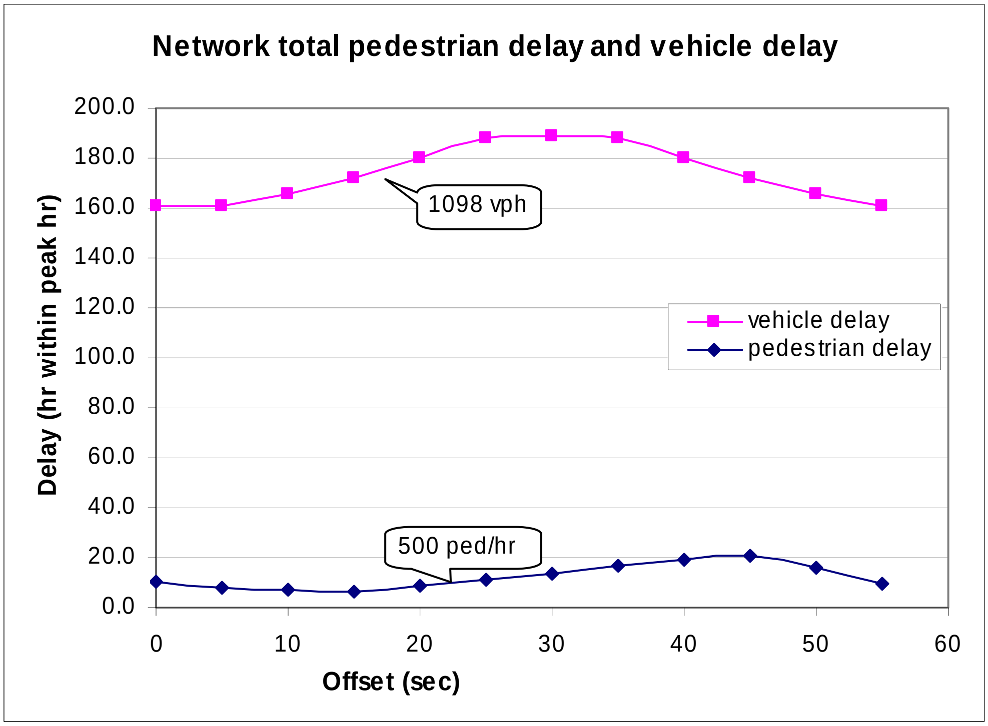


FIGURE 4-5: Variation in total pedestrian and total vehicle delay with change in offset

The delay curve for pedestrians in Figure 4-5 shows lesser difference between minimum and maximum delay than the delay curve for motor vehicles. If compared with the delay curves illustrated in Figure 4-5 for peak pedestrian and vehicle demand, there is a significant variation. This comparison is illustrated in Figure 4-6. The information in the figure suggests that a drop in pedestrian demand reduces the variation in total pedestrian delay.

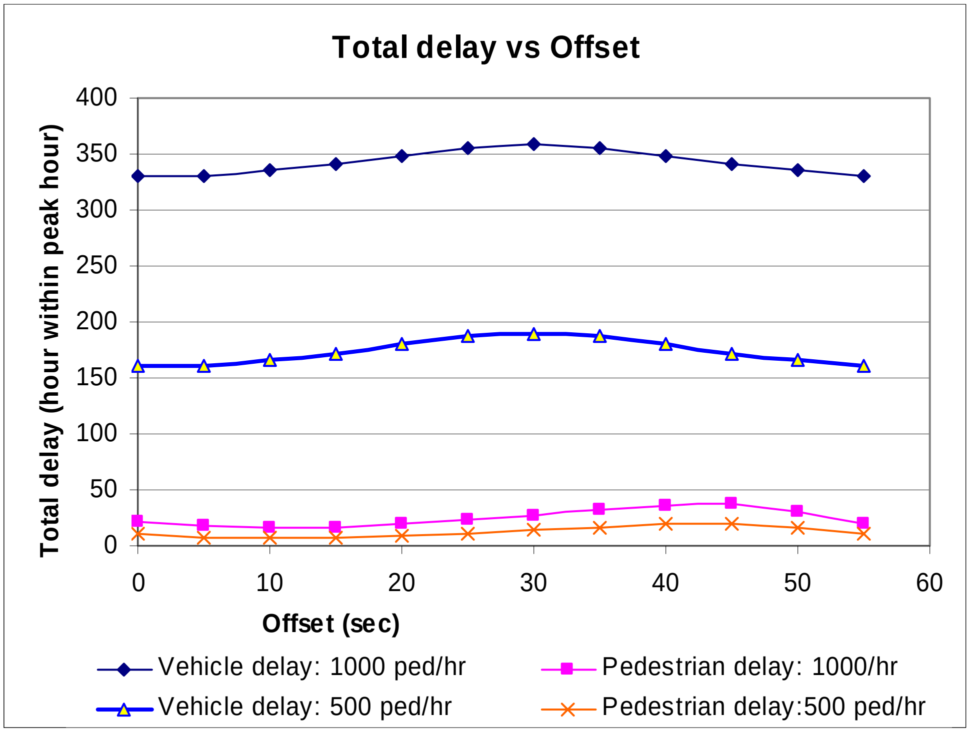


FIGURE 4-6: Comparison of total delay values for varying pedestrian volumes

As pedestrian volumes reduce, the variation in total delay lessens. This observation is derived from Figure 4-6 since the total delay curve corresponding to 500 pedestrians per hour is less undulating than that for 1000 pedestrians per hour. The delay curves are developed based on the results of the case study described in Section 4.2.1 and Section 4.2.2.

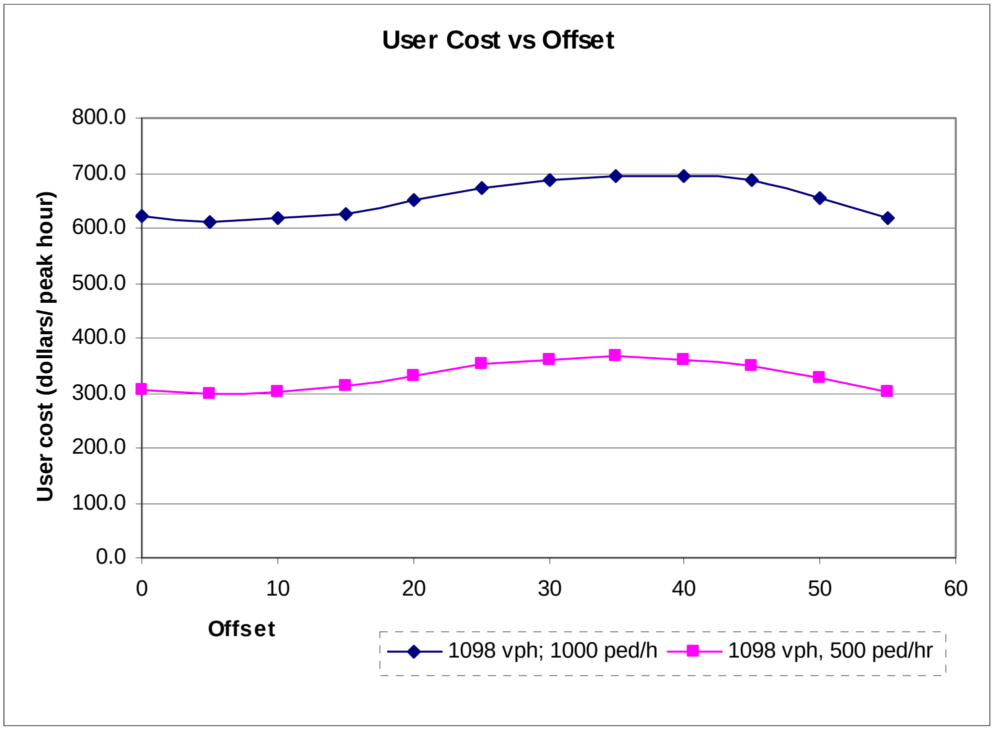


FIGURE 4-7: Comparison of user cost with different offsets for varying pedestrian volumes

Figure 4-7 indicates that the user cost reduces by nearly 50% when the pedestrian volumes reduce. This indicates that pedestrian delay comprises a significant portion of the user cost. Another traffic model is analyzed with a low pedestrian demand of 100 pedestrians per hour keeping the vehicle demand same as before. Details about the results of this analysis are provided in Appendix B. Using the delays obtained, the user costs for three scenarios for three pedestrian demand levels are compared. This comparison is illustrated in Figure 4-8.

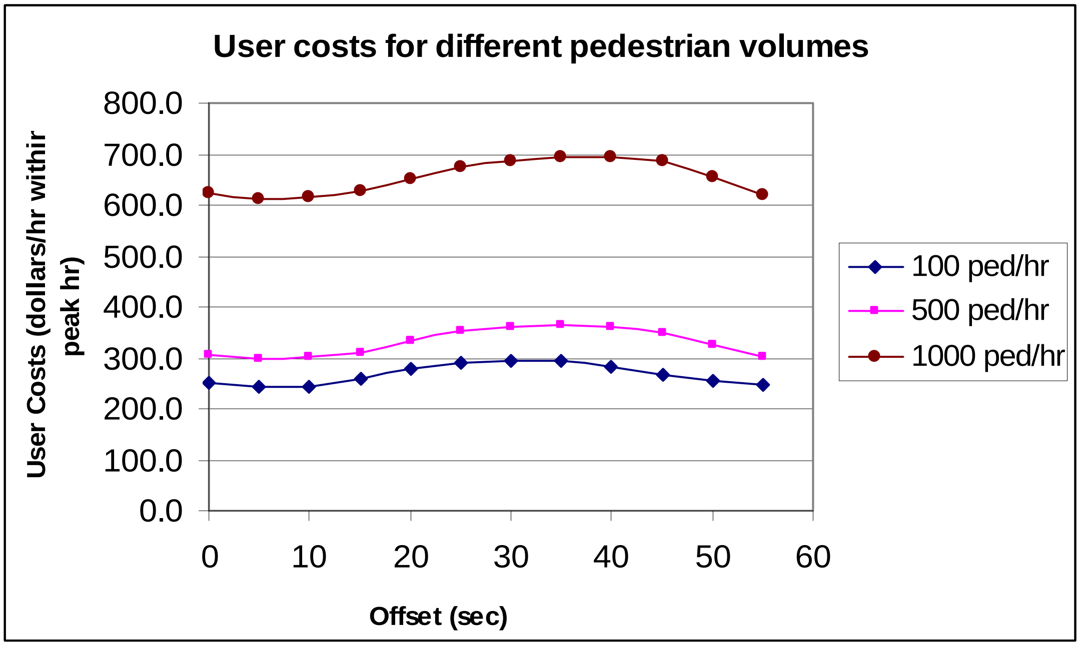


FIGURE 4-8: Effect of increasing pedestrian volumes on the user cost for different offsets

It is apparent from Figure 4-8 that pedestrian demand affects the user costs significantly. There is significant increase in user costs with rise in the pedestrian volumes. Not considering pedestrian delay in design calculations can reduce the benefits of traffic signal coordination to travelers and consequently, to the traffic agency. Among the scenarios tested, the one with the lowest pedestrian volume, that is, 100 pedestrians per hour, yields the lowest user costs, as expected. The difference in user costs for corresponding offsets between pedestrian demand volumes of 1000 and 500 pedestrians per hour is more than 300 dollars per hour. This difference is more prominent than the difference of about 50 dollars per hour between pedestrian demand volumes of 500 and 100 pedestrians per hour.

4.2.3 Peak period traffic - Pedestrian travel time and vehicle travel time valued equally

The previous two sections discussed user costs in the network based on the notion that pedestrian delay is more cumbersome than vehicle delay. In this case, user costs are determined by considering the values of pedestrian travel time and vehicle travel time to be the same. The network parameters stated in Section 4.2.1 are adopted with similar characteristics. Delay values pertaining to the results of modeling the network (in Section 4.2.1) are used. The methodology is applied as in the previous situations. The information given in Table 4-1 to Table 4-6 is utilized to determine the user costs for this scenario and the results are presented in Figure 4-9.

TABLE 4-16: Determination of user costs (pedestrian delay valued equal to vehicle delay)

Offset	Total delay to vehicles (hr within peak hr), Da	Total delay to peds (hr within peak hr), Dp	Value of vehicle time, T_a (\$/hr)	Value of ped time, T_p (\$/hr)	Average vehicle occupancy	User cost for vehicles and peds (\$/hr)
0 sec	330.62	21.328	1.396	1.396	1.22	592.86
5 sec	330.92	17.288	1.396	1.396	1.22	587.74
10 sec	334.89	16.928	1.396	1.396	1.22	593.99
15 sec	341.6	16.288	1.396	1.396	1.22	604.52
20 sec	348.92	20.408	1.396	1.396	1.22	622.74
25 sec	356.24	23.648	1.396	1.396	1.22	639.73
30 sec	358.68	27.288	1.396	1.396	1.22	648.97
35 sec	356.24	31.548	1.396	1.396	1.22	650.76
40 sec	348.92	35.870	1.396	1.396	1.22	644.33
45 sec	341.6	37.861	1.396	1.396	1.22	634.64
50 sec	334.89	29.695	1.396	1.396	1.22	611.81
55 sec	330.92	19.850	1.396	1.396	1.22	591.32

Comparing the user costs in Table 4-16 and Table 4-8, it is observed that the variation in user costs with different offsets follow the same pattern in both the cases. This is apparent from the user cost curves in Figure 4-12. A speculation can be drawn that there is no significant impact on progression when values of pedestrian travel times exceed those of vehicle travel times. However, it is a reflection of this case study and the speculation should be explored further for confirmation.

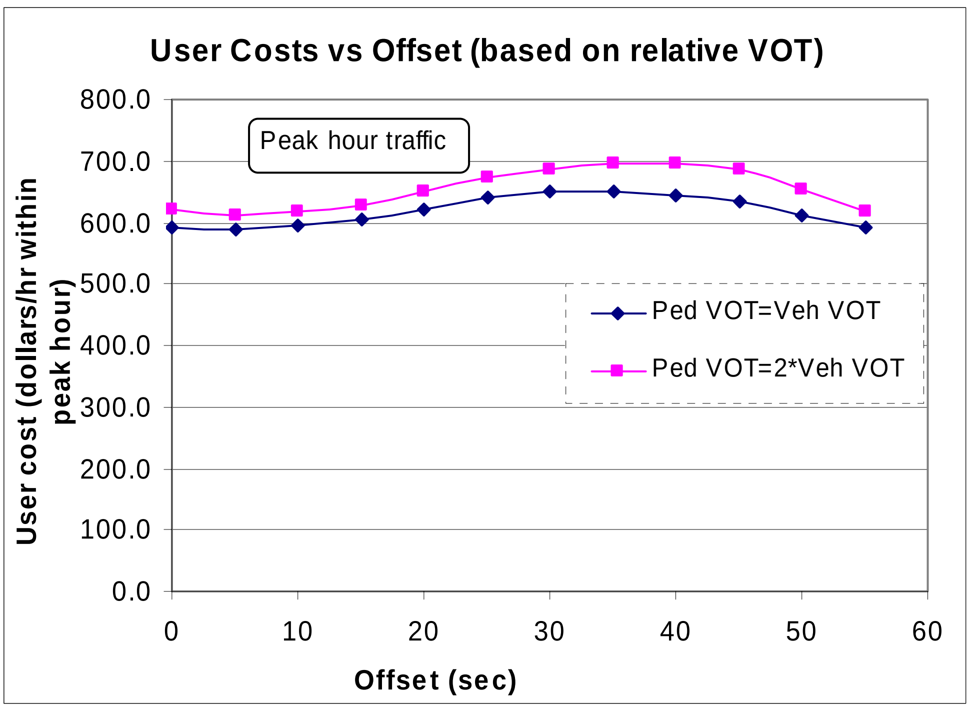


FIGURE 4-9: Comparison of user costs based on relative valuation of pedestrian delay and vehicle delay

If pedestrian value of travel time exceeds that of vehicle travel time, the user cost is not significantly different than the user cost if the travel times were valued equally. This observation is drawn from Figure 4-9.

4.2.4 Comparison of delays obtained from the analyses with HCM methods

Synchro 3.2 can optimize signal timings and coordinate traffic signals. Arterial level of service classification conforms to the arterial streets standards set in HCM. However, for saturated or oversaturated conditions, Synchro applies the Percentile Delay method to calculate the delays (described in Appendix). The HCM defines progression in terms of the arrival type or the proportion of vehicles arriving on green. This concept is described in detail in Section 2.1.2. This section aims to describe the delays obtained from Synchro in the light of HCM progression theory. Two model analyses are performed, one with high vehicle volume, and another with low vehicle volume. The delays to vehicles with change in the green to cycle time (g/C) ratio is observed. The input volumes for the two runs are displayed in Table 4-17 and Table 4-18 respectively. The comparisons of the two analysis results with HCM progression are described in Figure 4-10 and Figure 4-11.

TABLE 4-17: Input data for model analysis 1 with high vehicle volumes

All Nodes	EB			WB			NB			SB		
	L	Th	R	L	Th	R	L	Th	R	L	Th	R
	60	978	60	60	978	60	60	300	60	60	300	60
Conflicting pedestrians	1000		1000	1000		1000	275		275	275		275

For each g/C ratio, vehicle delay for a range of offsets (as described in the previous sections) is analyzed. The delay ratio is derived from the ratio of the minimum delay for an offset to the average delay for all offsets. Accordingly, a data set containing g/C ratios and corresponding delay ratios is obtained. A curve is plotted with delay ratio as the ordinate and g/C ratio as the abscissa. This curve is depicted in Figure 4-10.

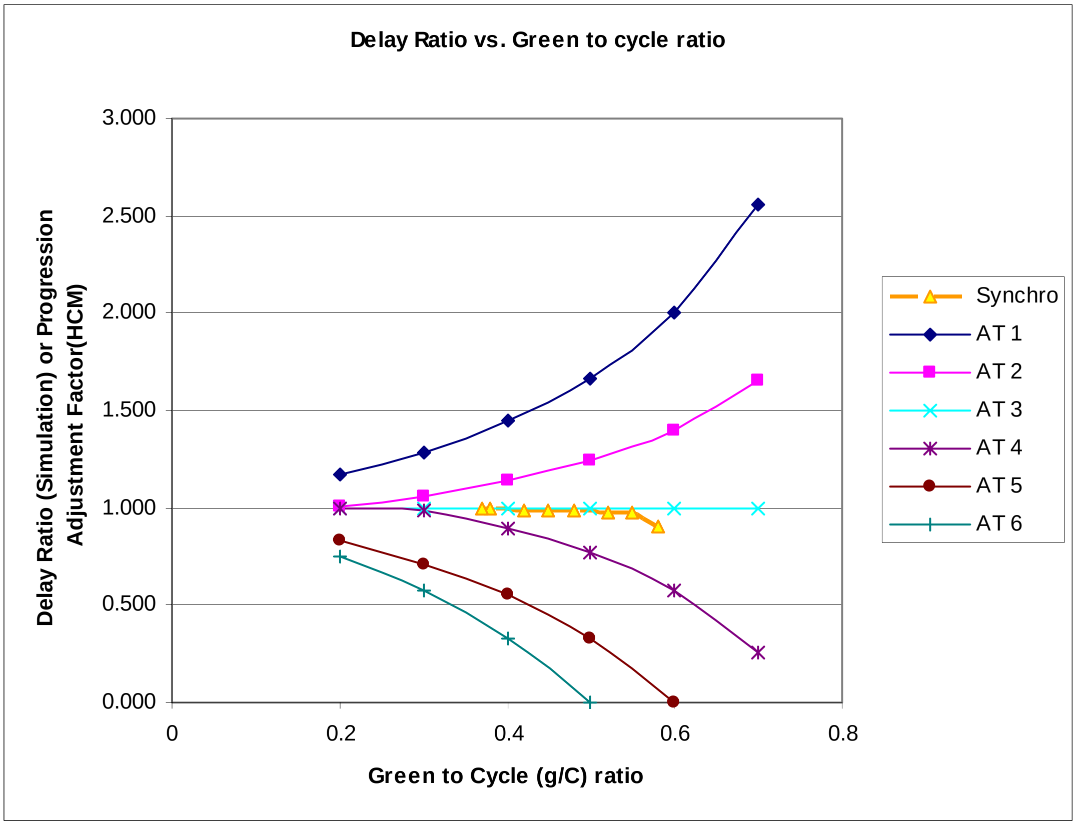


FIGURE 4-10: Comparison of Synchro progression and HCM progression by delay adjustment factor (peak traffic)

Figure 4-10 is based on the concept of Table 2-1 that shows progression adjustment factors, also called delay factors for different g/C ratios in terms of vehicle arrival type (AT). Table 2-1 is a copy of Exhibit 16-12 in HCM 2000. The data from the table is plotted on a graph to display curves for various arrival types. The delay ratios from the analysis are compared with the PF curves in the HCM. The delay ratio is close to one and the curve appears to be in tandem with the AT 3 curve between g/C ratios of 0.37 to 0.55. According to the HCM, arrival type 3 indicates random arrivals, for which the benefits of progression are minimal (details in Section 2.1.2). A delay adjustment factor of one implies that the uniform delay component is not affected by progression. For the case study, motor vehicle congestion may possibly occur due to the high traffic demand. Signal coordination would be of little benefit to vehicles in these circumstances. The delay ratio appears to bear some correlation to the delay adjustment factor in the HCM. In Figure 4-10, the delay ratio drops below unity beyond a g/C ratio of 0.5. The reason could be that an increase in the green time causes Synchro to reduce the main street delay. The delays being considered are arterial delays, which do not account for delays to vehicles trying to cross the main street from the side streets. Hence a greater green time would allow more vehicles to pass through the intersections and clear initial queues.

Table 4-18 contains the input data for model analysis 2. The vehicle volumes are low compared to model analysis 1 in this section. Pedestrian flow parameters remain the same. This is aimed at locating the progression pattern during off-peak traffic.

TABLE 4-18: Input data for model analysis 2 with low vehicle volumes

All Nodes	**EB**			**WB**			**NB**			**SB**		
	L	**Th**	**R**	**L**	**Th**	**R**	**L**	**Th**	**R**	**L**	**Th**	**R**
	60	600	60	60	600	60	60	300	60	60	300	60
Conflicting pedestrians	1000		1000	1000		1000	275		275	275		275

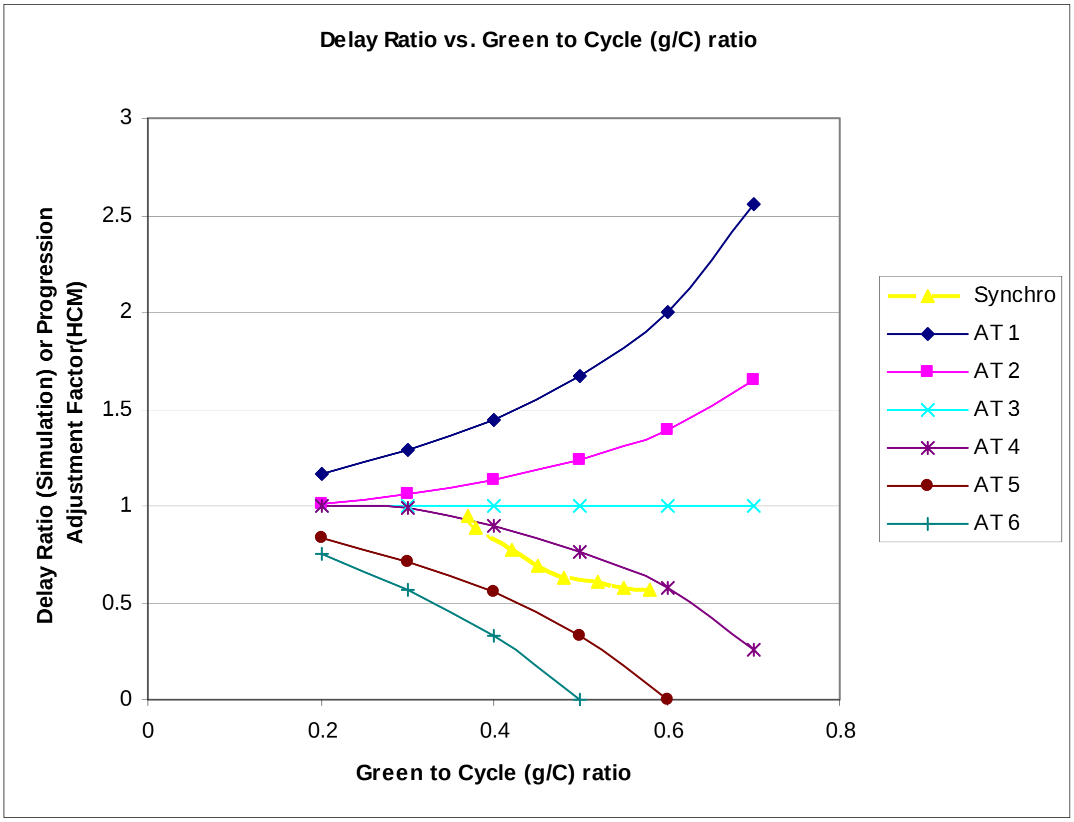


FIGURE 4-11: Comparison of Synchro progression and HCM progression by delay adjustment factor (off-peak traffic)

The delay ratios for green to cycle (g/C) ratios from 0.38 to 0.6 lie between the curves indicating AT 4 and AT 5, as observed in Figure 4-14. In HCM methodology, arrival type 4 and arrival type 5 are both favorable for progression. The delay ratio curve indicates that in this traffic scenario, signal coordination would benefit motor vehicle progression.

4.3 Discussion on Results

Table 4-8 shows that the best offset for vehicles does not necessarily yield the minimum user costs to the network, thereby suggesting that vehicles should not always be the only mode considered when coordinating signals. The best offset for pedestrians or vehicles is not necessarily the same as that for the minimum user cost, confirming that the optimal signal coordination plan should balance delays to the two modes.

Benefits due to the optimal signal coordination plan will occur to both short and long distance travelers. However, there may be significantly more short-distance travelers than long distance travelers in a central business district area. Short distance travelers are usually associated with work or commuting trips and long distance travelers with average trips. The value of vehicle travel time as laid down in the AASHTO Manual (1977) is based on two types of trips, average and work. The travel time value for a work trip is illustrated in Table 4-8, and the user cost has been computed using the value for the work trip given in the AASHTO Manual.

Our analyses also assumed that the relative value of pedestrian travel time exceeds that of vehicle travel time. If the values are assumed the same, there is no substantial change in the general observation. A case study supporting this view is given in Section 4.2.3. Economic benefits can still be achieved by accounting for pedestrian delay in the signal coordination plan. It would be useful to study the effect of including the relative travel time values of commercial and freight traffic. Future research could attempt to incorporate commercial traffic.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

5.1 Inferences on Case Study

The results of the case study in the previous chapter plainly reveal the economic benefits of considering both vehicle and pedestrian delay in a signal coordination plan. Signal coordination plans along a corridor should account for pedestrian progression since it significantly affects network delay. **Table 4-6** shows that there is a difference of 15 seconds between the best offset for pedestrians and the best offset for vehicles when pedestrian volumes are high. In such a situation, the engineer may have to consider a timing plan incorporating pedestrian requirements to enable pedestrians to benefit from signal coordination. As pedestrian volumes increase, the importance of considering pedestrian delay increases.

5.2 Discussion on Methodology

The methodology developed to provide better signal coordination could be a handy tool for a traffic engineer. It is based on sound traffic engineering principles with the aim of providing good progression for all travelers. As stated in Chapter 3, it is most applicable in transportation networks with high pedestrian movement. There are many locations in an urban area where such conditions may exist. A corridor in a central business district area provides an instance of such a location. Current practice in signal coordination does not accommodate pedestrian progression. The focus is on vehicular progression. Therefore, a new approach for traffic engineers or professionals would be to provide a balance between pedestrian progression and vehicular progression. The results of the case study affirm that the approach in this research improves the efficiency of the network. Network modeling using well-known traffic analysis software and a field-tested procedure for pedestrians combine to give rise to a logical methodology. The study considers two traffic modes and the overall impact of signal coordination on traffic operations. The methodology implicitly follows Highway Capacity Manual (HCM) procedures for analysis of delay. The delay ratios calculated for the pedestrian and vehicle movements are intended to compare with the Progression Adjustment Factor (PF) in the HCM.

A thorough literature review revealed that there has been little or no research along these lines. The method developed is unique in the sense that both pedestrians and automobiles receive the potential benefits of progression through signal coordination.

5.3 Conclusions

As shown in the case study, the offset with the lowest total vehicle delay is not necessarily the same as the offset corresponding to the lowest user cost accounting for pedestrian traffic. Paramount to maintaining vehicle throughput and efficiency, signal coordination should provide good progression to all modes of traffic on the roadway. These desirable features are reflected in the methodology, which delivers a rational decision framework to traffic engineers and decision-makers involved in providing signal coordination. It considers two modes, pedestrians and vehicles, and analyzes the delay patterns to arrive at a signal coordination plan that enhances progression on the corridor. Further research can be done to extend the methodology to include other competing modes of traffic on the roadway corridor. The rationale is to provide signal coordination not just to benefit vehicles alone; instead to adopt a multimodal perspective. The lowest user cost corresponds to low vehicle delay as well as low pedestrian delay. It is evident from the case study that pedestrian delay can comprise a significant portion of the total delay to the network due to signalization. Efficiency in network traffic operations can be achieved with a multimodal approach to signal coordination. In the course of demonstrating the methodology, a technique to provide good progression to pedestrians is described. Virkler (2000) suggests that, "When pedestrian and vehicle volumes are comparable, there may be a net benefit in considering the delay of both pedestrians and vehicles." This research supports that hypothesis.

5.4 Contributions

The original goal of this research was to compare delay between modes and consider the potential benefits of signal coordination to two modes of travel in a network using a socio-economic approach. The methodology developed can be adopted by traffic agencies or professionals to address transportation issues that have potential for good progression. It is expected to contribute towards the mitigation of congestion-related problems such as deterioration of air quality. This new approach to provide good progression adds to the existing body of knowledge on traffic signal coordination. Current transportation planning policies underline the importance of non-motorized transport and preservation of the existing transportation system. Thus, this approach provides a feasible alternative to capacity improvements by effectively addressing congestion or congestion-related problems.

5.5 Future Research

It would be beneficial to perform further research in this field. Research should extend the methodology to make it more effective and applicable to a wider range of traffic networks including highways.

- *Field implementation of Methodology*

Another area for further research is the field implementation of the research method. According to the HCM, model calibration is paramount to implementation of any method that uses modeling software. The signal settings recommended by the method would have to be validated through field implementation.

The case study uses software to study the traffic environment and the results on vehicle travel behavior were obtained from the analysis. Unless the methodology is implemented in a real-world situation, its benefits are not proven. There is significant evidence that pedestrians adjust their speeds according to signal timing patterns through prior experience to reduce delays. Thus, posting a progression speed in the network and conducting a test project would be a logical future step. A field study in a suitable site in the nature of a 'before' and 'after' study would be ideal. Chapter 3, Section 3.1 describes in detail the characteristics of a suitable site for the implementation of the methodology. Observations of delays and stops in the 'before' and 'after' situations would help in the assessment of pedestrian benefits. In the 'before' study, there would be no application of the method. The current traffic signal timings in the study area would apply. Traffic studies would have to be made at the intersections to determine vehicle and pedestrian volumes. Delays could be observed using the 15 minute interval and at 5 second increments within the interval. In the ‘after’ study, the optimal signal timings obtained from the traffic software could be applied to the study area under consideration. Traffic studies similar to the ‘before’ study would be performed to obtain the desired travel parameters. Total delay and average delay for various offset combinations would then be computed and user costs for the entire study area would be calculated accordingly. A detailed comparison of the parameters from the two studies would illustrate the effectiveness of the method. Variation in user costs compared to the ‘before’ study would reflect the efficiency of the methodology. A benefit/cost analysis could also be performed to confirm the validity of the method. Measures required would include capital costs, operation and maintenance costs, and benefits in terms of change in user costs.

- *Extension of corridor to a grid/network*

The case study involves traffic movement within a corridor, which may be a part of a network. With adequate care, the arterial corridor depicted in the case study could be expanded to a network or grid of interconnected streets. Chapter 4 describes a relevant example to demonstrate the methodology with good results. For additional benefit, the arterial example could be extended to a larger network. The methodology could be applied to a suitable grid or network and thus optimization of user costs could be achieved. This is a suggestion and further research on this aspect is required to verify its reasonableness.

- *Consideration of other modes*

This research focuses on pedestrians and vehicles, and particularly corridors where these two modes are predominant with significant volumes. Pedestrians and vehicles may not be the only travelers in the network, as the route may also be carrying transit vehicles or bicycles. There may be locations with significant volumes of modes such as bus transit or bicycles. In fact, multimodal corridor analysis should involve all modes traveling through the corridor. Further research in this area could include these considerations. The following paragraphs elaborate on the undergoing research in this area. Transit vehicles are associated with frequent stops for loading and unloading of passengers, fixed schedules, and fixed routes. According to the Transit Capacity and Quality of Service Manual (1994), bus transit stop locations affect vehicle capacity, primarily when right turn movements by passenger vehicles are allowed from the curb lane. However, there are other considerations in selection of a bus stop location such as potential conflicts with other vehicles operating on the street, transfer opportunities, the distances passengers must walk to and from the bus stop, locations of passenger generators, signal timing, driveway locations, physical obstructions, and the potential for implementing transit preferential measures.

Presence of transit facilities in the network would require estimation of measures of transit service operations including travel times and capacity. Chapters 17, 27 and 29 of the HCM contain elaborate methods and calculations for evaluation of such measures. Chapter 29 on corridor analysis focuses primarily on transit operations on the urban street, excluding pedestrian and bicycle facilities. Regarding transit vehicle progression, signal priority for bus transit, better known as Transit Signal Priority (TSP), is a major research area and has been effectively implemented in several cities. The city of Portland in Oregon is one example where the transit agency has tested strategies to provide signal coordination benefits to transit. A study conducted by the National Center for Transit Research (NCTR) (2001) on various bus signal priority strategies used by various agencies within the US revealed interesting results. In some cases, these studies involved adaptive control systems, the TSP being called active priority. For fixed-time signal controls and scheduled-based transit, passive priority is recommended. One study concluded that reduction in transit delay was not sufficient to counteract the overall impact on traffic operations. In general, the effectiveness of TSP depends on the control system chosen for a particular corridor. According to Garrow and Machemehl (1997), the success of transit signal priority systems are highly contingent on the specific characteristics of each network.

Commercial traffic such as freight vehicles are not considered to be a significant presence in the case study. This may not necessarily be the case and hence, future research could address the impact of signal coordination on commercial and freight traffic progression.

Bicycle movement in a corridor may be facilitated by bike routes, or bike lanes. Methods for providing good progression for bicycles would assist traffic engineers in coordinating traffic on busy multimodal corridors. In the US, Mahmassani (2000) has conducted seminal research in the field of bicycle progression. Methods to solve the problem of coordinating traffic signals to benefit both bicycles and vehicles are discussed. A multiobjective framework is formulated to provide progression to bicycles as well as the competing vehicular traffic on multimodal streets. Factors affecting bicycle progression are elucidated. Short street segments, closely spaced intersections, high bicycle volumes, and low speed variability are likely to promote the chances of bicycles to benefit from signal coordination. Bicycle traffic is a dominant mode on mixed roads in European cities. However, in the US, bicycle movement on the main city streets is not as common as in Europe. Several cities have bicycle routes and/or bike paths but usually, these are separate facilities not integrated with mainstream traffic in busy urban streets.

- *Method utilizes real-time traffic control*

The method developed in the research assumes fixed-timed signal control. The aim was to devise a cost-effective approach to alleviate traffic congestion on particular corridors. If sufficient funds are available then a traffic adaptive signal control algorithm that considers both pedestrians and vehicles can be developed to alleviate delay. An economic efficiency analysis can be done to verify the benefits of implementation. A FHWA sponsored study by Hughes et al (2001) on automated pedestrian detection at signalized intersections evaluates the use of infrared, microwave, and video image processing at several selected sites. Pedestrian movement and arrivals may be detected using these technologies. The study suggests that these advanced technologies can provide significant operational and safety benefits when applied in conjunction with the traditional pedestrian push-buttons at actuated signals. Currently, further possibilities are being investigated. A study reported in the latest TRB conference by Bechtel et al (2004) suggests ITS-based technologies to tackle pedestrian safety and prevent injuries. This research can assist studies in this field with progression and delay analysis.

For instance, Urban Traffic Optimization by Integrated Automation (UTOPIA) is an active real-time TSP system. It considers non-transit vehicles, along with transit vehicles, within a hierarchical decentralized traffic adaptive control system. The total travel time is optimized subject to constraints of average speed and saturation flows. Problems are classified into a lower level (at the intersection) or a decision level (over the entire area). The field trial of the enhanced SPOT system performed in Leeds, England reduced travel time by approximately 10 percent. Non-transit vehicle travel times were unchanged. A similar strategy for real-time signal control system to better coordinate traffic signals for both pedestrians and vehicles would be very useful indeed.

- *Application of TSIS and HCS software*

It might be useful to utilize some other software programs such as TSIS or HCS in addition to Synchro. Synchro provides optimized signal timings based on the input traffic and geometric characteristics. CORSIM is part of the TSIS package and contains the NETSIM and FRESIM microscopic simulation models. CORSIM is the corridor simulation model where vehicles move according to car-following logic, in response to traffic control devices and demand. Simulating the same traffic environment in CORSIM, these timings can be applied while entering the traffic control data into the program. The author performed this step to check the delay values for different offsets. However it was seen that for heavy traffic, simulation on CORSIM yielded delay values that were considerably lower than Synchro values, though spillback was observed on various links at various times. Due to limited resources of time and data, the problem could not be dealt with in detail. The scope of the research is not limited to only one simulation program but can be extended to include other relevant programs. The optimized signal timings obtained from Synchro 3.2 can also be tested in a similar fashion using HCS 2000 software. The limitations of the 'Signals' tool in HCS 2000 are that it works for one intersection at a time and requires the user to enter the arrival type or proportion of vehicles arriving on green. It generates delay values based on HCM 2000 specifications. Options to coordinate signals and apply signal coordination plans exist in the HCS 'Arterial' tool but are limited in scope. Urban streets are classified by type based on access density, pedestrian activity, signals per mile, speed limit etc. The signal intersection data files created by using 'Signals' feature could be imported into the HCS 'Arterial' software. These intersections could then be connected by user-defined segments. The length and the urban street class for each segment need to be defined to build the network or corridor. HCS could then perform corridor analysis with output measures such as control delay, running time, arterial speed and LOS. The case study demonstrated in Chapter 4 with signal timings optimized by Synchro is analyzed with the optimal signal timings on HCS 2000. The output includes arterial delay and arterial LOS. It is observed that HCS yields lower arterial delay values and lower volume to capacity ratios than Synchro. Regarding the network for which the method is recommended, it is assumed that the arrivals are random at the entry nodes. Though significant platooning can be expected to occur as the vehicles progress through the corridor, it is difficult to predict the arrival type.

Interesting research could be done using three types of software programs discussed in the previous paragraph. The user could create and optimize the network on Synchro. The same network could be simulated on CORSIM using the optimized signal timings from Synchro. CORSIM simulates delay for each link in the arterial and also yields simulation output such as vehicle throughput and control delay. The individual intersections could be created on HCS software assuming different arrival types. The signal timings suggested by Synchro can be implemented on HCS 'Signals' feature. The signalized intersections created could be extended into an arterial using the 'Arterials' tool. The arterial delays obtained can be compared to observe the variation in calculation and working of the two software packages. HCS 'Arterial' software could then be used to observe the arterial-based output measures. Comparison of various output parameters such as delay, travel times, fuel emissions could yield interesting observations. This would be a useful addition to the existing body of knowledge on traffic progression and signal optimization. There have been attempts in the past to compare arterial delays by simulation using different programs. In a recent study, Benekohal et al (2002) compared delays obtained from HCS, Synchro, PASSER II and IV and CORSIM simulation of urban arterials. The simulation delays from the software programs were evaluated under two conditions, the base condition and the optimized condition. CORSIM was used to compare four scenarios, the optimized conditions obtained from the simulation on Synchro and PASSER II and IV and the base condition simulated in CORSIM. Network delay for Synchro was observed to be slightly less than the delay for the other three simulated scenarios. The traffic volumes simulated pertain to the peak period. However, details about the traffic input volumes were not indicated by the study.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO) (1977), A Manual on User Benefit Analysis of Highway and Bus Transit Improvements, FHWA.

Benekohal, R.F., Elzohairy, Y.M., and Saak, J.E. (2002), "Comparison of Delays from Highway Capacity Software, Synchro, PASSER II and IV and CORSIM for Urban Arterials", Transportation Research Record 1802, TRB, National Research Council, Washington D.C., 133-144

Chada, S. and Newland, R. (2002), "Effectiveness of Bus Signal Priority-Final Report", Report No. NCTR-416-04, National Center for Transit Research (NCTR), University of South Florida, Tampa, Florida.

Clark, S.D. and Page, M. W. (2003), "Cycling and Urban Traffic Management and Control Systems", Transportation Research Record 1705, TRB, National Research Council, Washington D.C., 77-84

Flannery, A., Anderson, A., and Martin, A. (2004), "The Use of HCM/HCS 2000 and Advanced Modeling Tools: Focus Group Findings", Transportation Research Board Annual Meeting 2004, Compendium of Papers (CD-ROM)

Garrow, M. and Machemehl, R. (1997), "Development and Evaluation of Transit Signal Priority Strategies", Southwest Region University Transportation Center Report No. SWUTC/97/472840-00068-1, http://ntl.bts.gov/lib/20000/20300/20367/PB98125065.pdf, Accessed March 1, 2004.

Ghassan, A. and Benekohal, R.F. (2000), "Signal Coordination and Arterial Capacity in Oversaturated Conditions", Transportation Research Record 1727, TRB, National Research Council, Washington D.C., 68-76

Hensher, D.A. (1998), "Value of travel time savings in personal and commercial automobile travel", Institute of Transport Studies, University of Sydney, Graduate School of Business.

Highway Capacity Manual: 2000 Edition, TRB, National Research Council, Washington D.C.

Hughes, R., Huang, H., Zegeer, C. and Cynecki, M. (2001), "Evaluation of Automated Pedestrian Detection at Signalized Intersections", FHWA Report No. FHWA-RD-00-097, http://www.walkinginfo.org/task_orders/to_11/peddetec.pdf, Accessed March 10, 2004.

Lomax, T. and Schrank, D. (2002), "Annual study shows traffic jams as a growing triple threat", Texas Transportation Researcher, Volume 38, Number 2.

May, A.D. (1990), "Traffic Flow Fundamentals", Prentice Hall, Upper Saddle River, N.J.

McLeod, Douglas S. (2002), "Multimodal Arterial Level of Service", Proceedings: Fourth International Symposium on Highway Capacity, Florida Department of Transportation.

National Survey of Pedestrian and Bicyclist Attitudes and Behaviors (2002), jointly sponsored by the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) and the Bureau of Transportation Statistics (BTS), Highlights Report, http://www.walkinginfo.org/pdf/FinalBikePedSurveyHighlightsReport_v2.pdf, Accessed March 19, 2004.

Noland, R.B. (1996), "Pedestrian Travel Times and Motor Vehicle Traffic Signals", Transportation Research Record 1553, TRB, National Research Council, Washington D.C., 28-33.

Noland, R.B. (2003), "Optimal Travel Time Trade-Offs at Signalized Pedestrian Crossings", Center for Transport Studies, Department of Civil and Environmental Engineering, Imperial College London.

Reid, J.D., Hummer, J.E. (1999), "Analyzing System Travel Time in Arterial Corridors with Unconventional Designs Using Microscopic Simulation", Transportation Research Record 1678, TRB, National Research Council, Washington D.C., 208-215

Roess, P.R., McShane, W. R., and Prassas, E. S. (1998), *Traffic Engineering*, Prentice Hall, Upper Saddle River, New Jersey.

N. Rouphail, J. Hummer, J. Milazzo II, and P. Allen (1998), "Capacity Analysis Of Pedestrian And Bicycle Facilities: Recommended Procedures For The "Pedestrians" Chapter Of The Highway Capacity Manual", Report No.FHWA-RD-98-107, Office of

Safety & Research & Development, Federal Highway Administration, 6300 Georgetown Pike
McLean, Virginia 22101-2296.Website: http://www.walkinginfo.org/task_orders/to_8/to8/chap13/title.htm

Small, K.A. (1992), *Urban Transportation Economics*, Harwood Academic Publishers: Chur, Switzerland.

Small, K.A., Noland, R., Chu, X. and Lewis, D.(1999), "Valuation of Travel-Time Savings and Predictability in Congested Conditions for Highway User-Cost Estimation", Transportation Research Board, National Research Council, NCHRP Report 431.

Tarko, Andrzej P. (2000), "Analyzing Arterial Streets on Near-Capacity or Overflow Conditions", Transportation Research Record 1710, TRB, National Research Council, Washington D.C., 231-238.

Taylor, D.B. and Mahmassani, H. S. (2000), "Coordinating traffic signals for bicycle progression", Transportation Research Record 1705, TRB, National Research Council, Washington D.C., 85-92

Virkler, M.R. (1998), "Signal Coordination Benefits for Pedestrians", Transportation Research Record 1636, TRB, National Research Council, Washington D.C., 77-82.

Virkler, M.R., and Chilukuri, V. (2003), "Pedestrian Progression: A Viable Alternative in Central Business Districts", Transportation Research Board Annual Meeting 2003, Compendium of Papers (CD-ROM).

Virkler, M.R. (1998), "Pedestrian Compliance Effects on Signal Delay", Transportation Research Record 1636, TRB, National Research Council, Washington D.C., 88-91.

APPENDIX A

DETAILS OF SYNCHRO MODELING AND OPTIMIZATION

As explained in Chapter 2, Section 2.2, Synchro Version 3.2 is a complete software package for modeling and optimizing traffic signal timings. A summary of its key features, as given in the Help Manual distributed with the software, is described.

Capacity Analysis

Synchro implements the methods of the 1994 Highway Capacity Manual; Chapter 9. In addition to calculating capacity, Synchro can also optimize cycle lengths and splits. All values are entered using form windows. Calculations and intermediate results are shown on the same forms. If the intersection is coordinated, Synchro explicitly calculates the platoon factor. Synchro calculates the effects of coordination automatically and accurately.

Coordination

Synchro can optimize phase splits, cycle lengths, and timing offsets. Synchro optimizes delays using an optimization process that minimizes delays for a given intersection. This makes timing plans in Synchro similar to TRANSYT which optimizes to reduce stops and delays. PASSER and other arterial software optimize to maximize the arterial bandwidth.

Percentile Scenarios

Over the course of an hour, traffic may not arrive at an intersection uniformly. Some cycles may have more traffic and some cycles may have less. A Poisson distribution can used to predict the arrival of traffic. To account for variations in traffic, Synchro models traffic flow under five percentile scenarios, the 90th, 70th, 50th, 30th, and 10th percentile scenarios. Thereby, if 100 cycles are observed, the 90th percentile cycle will be the 90th busiest cycle. Each of these scenarios will represent 20% of the cycles actually occurring. The traffic volumes for each scenario are adjusted up or down according to the following formulae. The expected number of vehicles, l, is the hourly flow rate divided by the number of cycles per hour.

$$l = A * C / 3600 = \text{vehicles expected per cycle}$$

where

A = Arrival Rate (vph)

C = Cycle Length (s)

The variance or standard deviation in traffic is the square root of the expected number of vehicles for a Poisson arrival.

$$r = \text{Sqrt}(l) = \text{standard deviation in expected arrivals per cycle}$$

The expected number of vehicles for a given percentile can be calculated using a Poisson distribution. A Normal Distribution can be used if the expected number of vehicles is greater than six (6). This gives the formula:

$$V_N = (l + z\,r) * 3600 / C = \text{Volume for Nth percentile (vph)}$$

where

C = Cycle Length (s)

z is the number of standard deviations needed to reach a percentile from the mean. It can be determined from this table.

Percentile	z
10	-1.28
30	-0.52
50	0
70	0.52
90	1.28

The simplified formula to determine adjusted volumes is thus:

$$V_N = A + z * \text{Sqrt}(A * C / 3600) * 3600 / C$$

Using five scenarios instead of one has several advantages. Even though an approach is below capacity, it may be above capacity for the 90th percentile traffic. By modeling the 90th percentile traffic, it is possible to better model nearly saturated intersections.

Optimization

Signal optimization is performed by Synchro with the aid of certain in-built features and tools. The relevant tools utilized by the case study demonstrated in the research are described below.

Optimize-Intersection Splits

The Optimize->Intersection-splits command will automatically set the splits for all the phases. Time allocation is based on each lane group's traffic volume divided by its adjusted saturated flow rate. If a lane group serves two or more movements, such as Through-and-Left or Through-and-Right, the sum of their volumes is divided by the sum of their lanes.

Optimizing Splits by Percentile

When optimizing splits, Synchro first attempts to provide enough green time to serve the 90th percentile volumes. If there is not enough cycle time to meet this objective, Synchro attempts to serve the 70th percentile traffic and then the 50th percentile traffic. Any extra time is given to the main street phases. By attempting to serve the 90th percentile, Synchro creates splits to clear the queue 90% of all cycles. Because low volume approaches have more variability in traffic than high volume approaches, this method will tend to give a lower volume to capacity (v/C) ratio for low volume approaches. This technique adopted by Synchro would be clearer considering the following examples.

Phase #1, volume = 120 vehicles per hour (vph), cycle length = 60 seconds, capacity is 1800 vehicles per hour (vph)

50th percentile volume per cycle is 2.

95th percentile volume per cycle is 4.3.

Green time assigned is 7 seconds

v/C ratio is 0.5

Phase #2, volume = 1000 vph, cycle length = 60 seconds, capacity is 1800 vph

50th percentile volume per cycle is 17.

95th percentile volume per cycle is 23.

Green time assigned is 46 seconds

v/C ratio is 0.7

In practice, percentile optimization gives short phases a few extra seconds to process an occasional extra vehicle. Longer phases also get extra time, but their extra time is less as a proportion of the total time. If the volume exceeds capacity, Synchro will attempt to give even v/C ratios to each phase, while still respecting all minimums.

Synchro modeling – Illustration of the input and output features

The windows that Synchro displays to assist the user with data entry for analysis and modeling are illustrated in Figures A-1 through A-3. The output window that shows arterial delay is shown in Figure A-4.

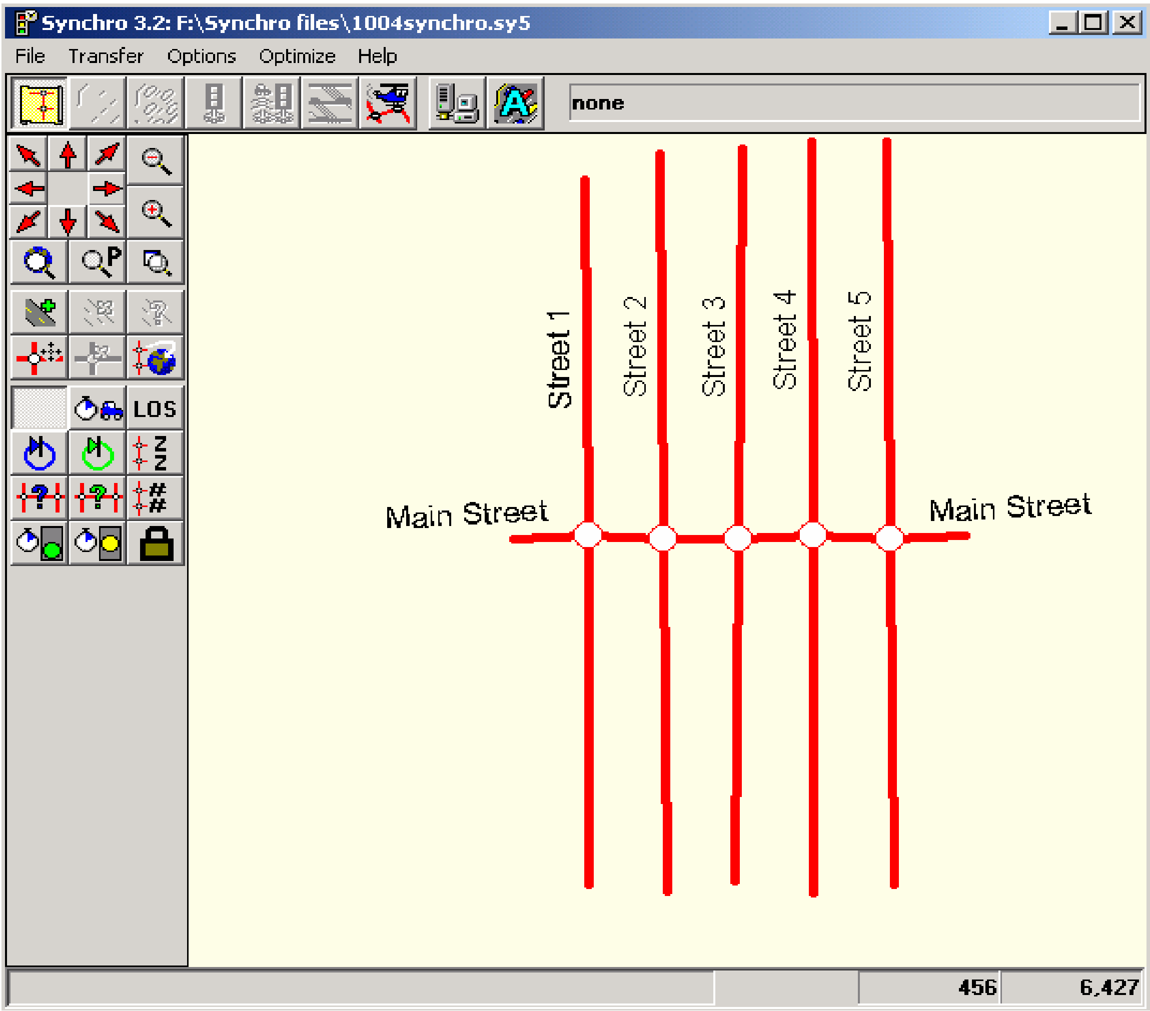
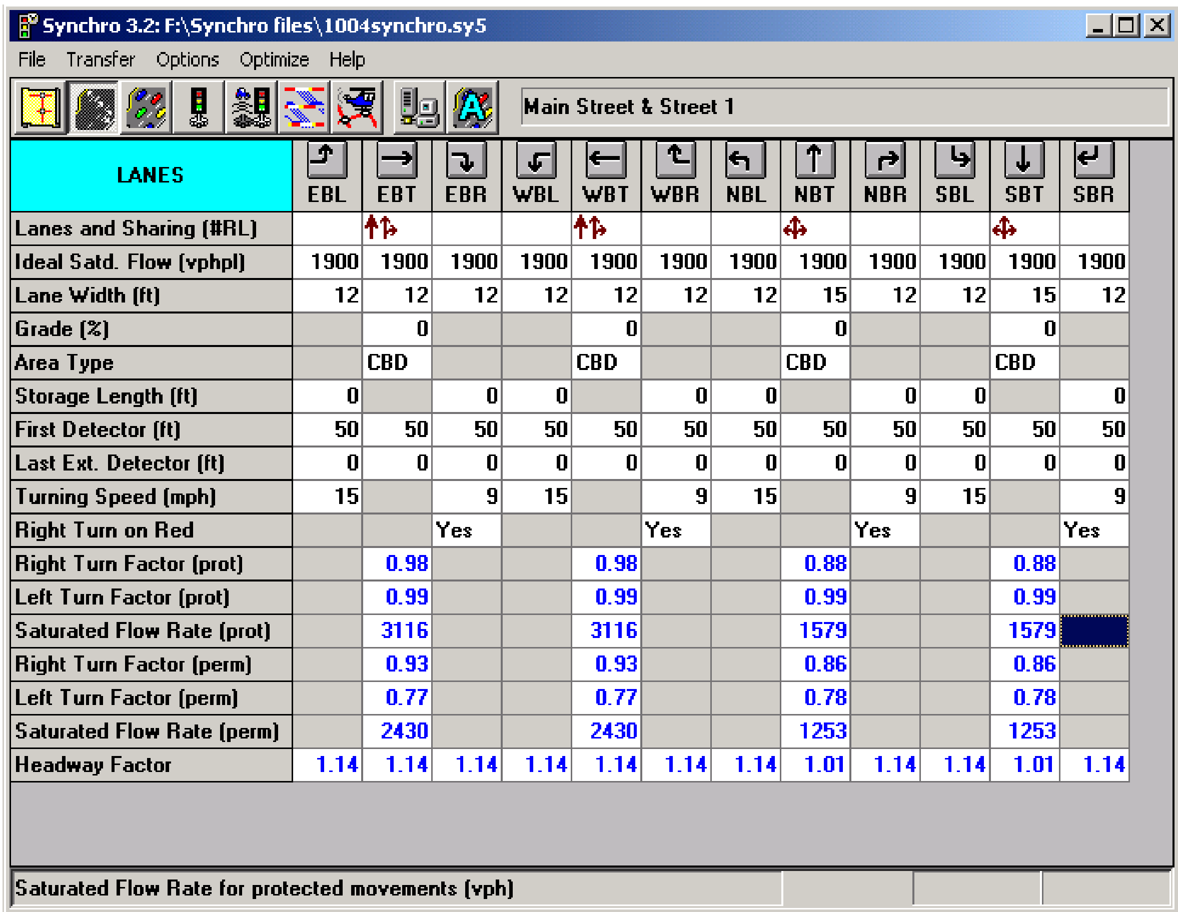


FIGURE A-1: Illustration of the case study network in SYNCHRO

An overview of the arterial network created on Synchro software is shown in Figure A-1. This window serves as the main screen for modeling. It enables easy navigation to the windows to enter the relevant data for flow, intersection geometry, lane geometry, parking etc The user builds the network on this window drawing the links and signalized nodes are created whenever cross streets are added to the network.

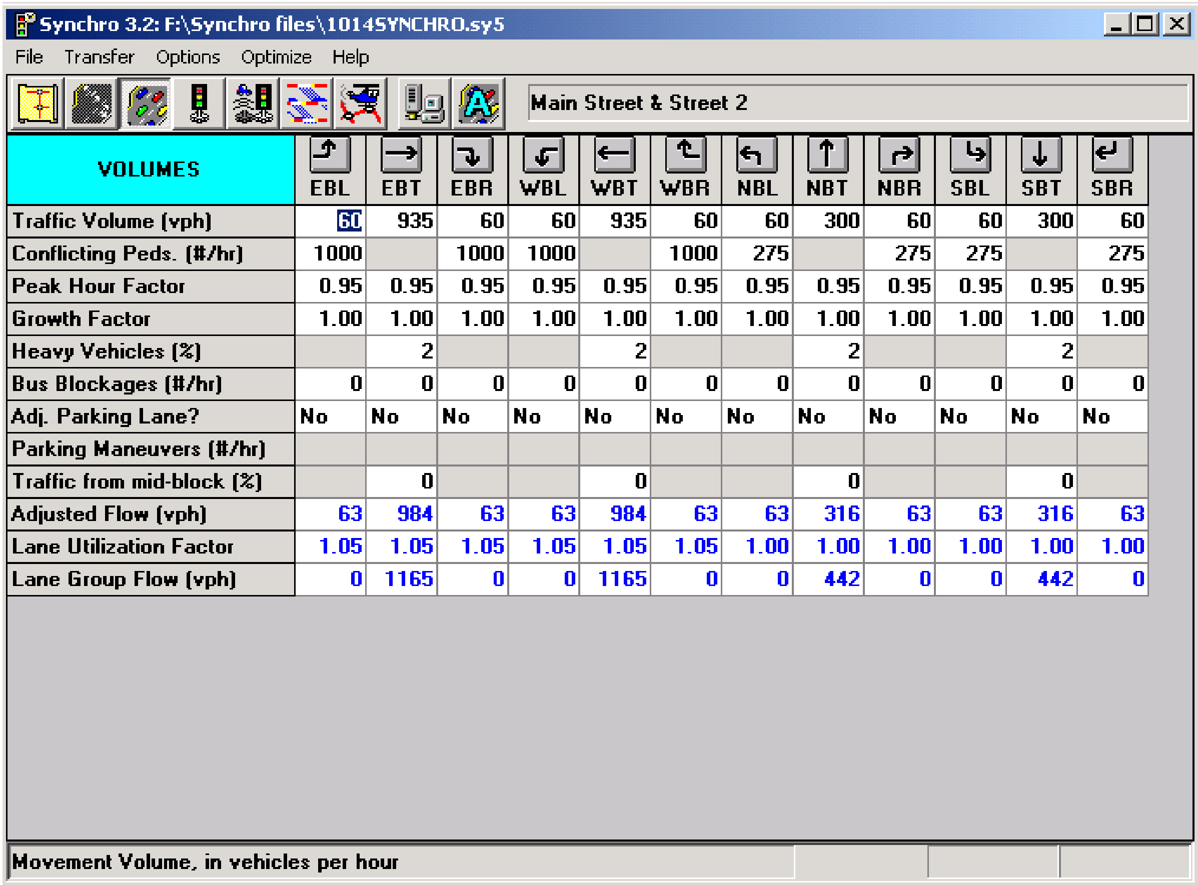
Information on lane geometry, grades, area type, detector information, right-turning vehicles and right-turn-on-red(RTOR) permission can be entered into the software using the 'LANES' window for each intersection as shown in Figure A-2.



LANES	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Lanes and Sharing (#RL)												
Ideal Satd. Flow (vphpl)	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900	1900
Lane Width (ft)	12	12	12	12	12	12	12	15	12	12	15	12
Grade (%)		0			0			0			0	
Area Type		CBD			CBD			CBD			CBD	
Storage Length (ft)	0		0	0		0	0		0	0		0
First Detector (ft)	50	50	50	50	50	50	50	50	50	50	50	50
Last Ext. Detector (ft)	0	0	0	0	0	0	0	0	0	0	0	0
Turning Speed (mph)	15		9	15		9	15		9	15		9
Right Turn on Red			Yes			Yes			Yes			Yes
Right Turn Factor (prot)		0.98			0.98			0.88			0.88	
Left Turn Factor (prot)		0.99			0.99			0.99			0.99	
Saturated Flow Rate (prot)		3116			3116			1579			1579	
Right Turn Factor (perm)		0.93			0.93			0.86			0.86	
Left Turn Factor (perm)		0.77			0.77			0.78			0.78	
Saturated Flow Rate (perm)		2430			2430			1253			1253	
Headway Factor	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.01	1.14	1.14	1.01	1.14

FIGURE A-2: View of the lane input window in Synchro

For each intersection, details about the flow of traffic, including percentage of heavy vehicles, parking, peak hour factors, and transit are entered utilizing the 'VOLUMES' window on the menu bar.

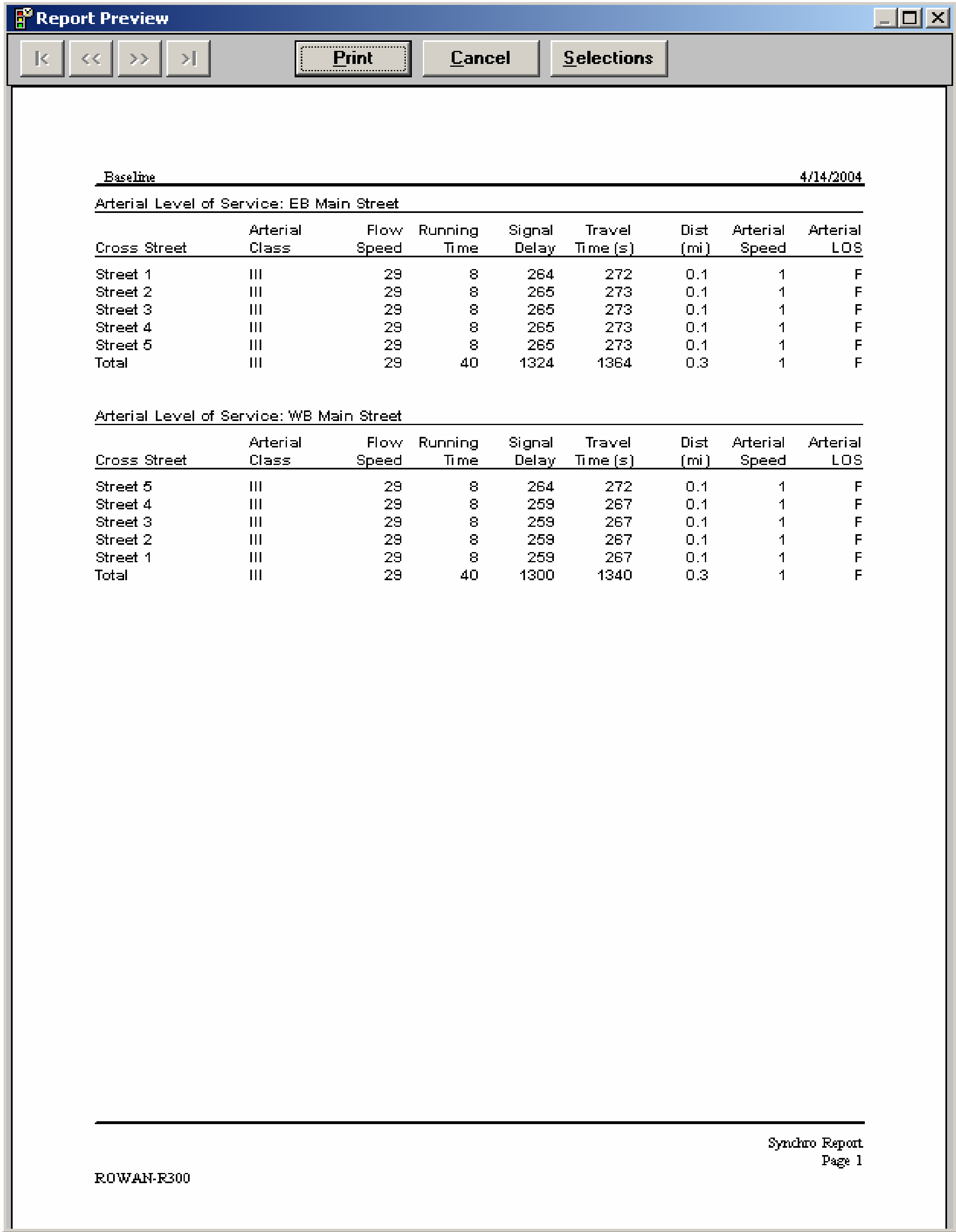


VOLUMES	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR
Traffic Volume (vph)	60	935	60	60	935	60	60	300	60	60	300	60
Conflicting Peds. (#/hr)	1000		1000	1000		1000	275		275	275		275
Peak Hour Factor	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Growth Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Heavy Vehicles (%)		2			2			2			2	
Bus Blockages (#/hr)	0	0	0	0	0	0	0	0	0	0	0	0
Adj. Parking Lane?	No	No	No	No	No	No	No	No	No	No	No	No
Parking Maneuvers (#/hr)												
Traffic from mid-block (%)		0			0			0			0	
Adjusted Flow (vph)	63	984	63	63	984	63	63	316	63	63	316	63
Lane Utilization Factor	1.05	1.05	1.05	1.05	1.05	1.05	1.00	1.00	1.00	1.00	1.00	1.00
Lane Group Flow (vph)	0	1165	0	0	1165	0	0	442	0	0	442	0

FIGURE A-3: View of the traffic volumes window in SYNCHRO

Figure A-3 shows traffic volumes specified by type of movement. Synchro requires pedestrian volumes to be input as the volumes conflicting with the turning vehicles. Information on flow variations during the day, especially for the peak period traffic, need to be specified.

Figure A-4 is an illustration of the arterial report window showing various output measures such as arterial delay, arterial level of service, average travel speed.



Baseline 4/14/2004

Arterial Level of Service: EB Main Street

Cross Street	Arterial Class	Flow Speed	Running Time	Signal Delay	Travel Time (s)	Dist (mi)	Arterial Speed	Arterial LOS
Street 1	III	29	8	264	272	0.1	1	F
Street 2	III	29	8	265	273	0.1	1	F
Street 3	III	29	8	265	273	0.1	1	F
Street 4	III	29	8	265	273	0.1	1	F
Street 5	III	29	8	265	273	0.1	1	F
Total	III	29	40	1324	1364	0.3	1	F

Arterial Level of Service: WB Main Street

Cross Street	Arterial Class	Flow Speed	Running Time	Signal Delay	Travel Time (s)	Dist (mi)	Arterial Speed	Arterial LOS
Street 5	III	29	8	264	272	0.1	1	F
Street 4	III	29	8	259	267	0.1	1	F
Street 3	III	29	8	259	267	0.1	1	F
Street 2	III	29	8	259	267	0.1	1	F
Street 1	III	29	8	259	267	0.1	1	F
Total	III	29	40	1300	1340	0.3	1	F

Synchro Report
Page 1

ROWAN-R300

FIGURE A-4: Arterial Report window displaying various output flow measures

APPENDIX B

DESCRIPTION OF RESULTS FROM ANALYSIS

Some more scenarios were analyzed in the course of the research to compare with traditional methods of computing delay and to examine the potential for additional information on delay and progression. Collaterally, the consistency of delays output by Synchro with different traffic volumes for the same study network can be observed. These are discussed in this Appendix. In continuation to Chapter 4, Section 4.2, this appendix also provides detailed information on the analysis results including raw output measures. The supporting data to the curve plotted in Figure 2-1 in Chapter 2, Section 2.2 is tabulated and described in Scenario 3. Scenario 1 is utilized in Section 4.2.4, where the comparison of Synchro progression and HCM progression by delay measures is shown in details with input data and results.

SCENARIO 1: (in Section 4.2.4)

Objective: To observe a situation with low vehicle demand and high pedestrian volumes

Volumes:

TABLE B-1: Input volumes for modeling Scenario 1

All Nodes	**EB v/c ratio=0.75**			**WB v/c ratio=0.75**			**NB v/c ratio= 0.77**			**SB v/c ratio= 0.77**		
	L	**Th**	**R**	**L**	**Th**	**R**	**L**	**Th**	**R**	**L**	**Th**	**R**
	60	600	60	60	600	60	60	300	60	60	300	60
Conflicting pedestrians	1000		1000	1000		1000	275		275	275		275

The input volumes in Table B-1 are referred to as high pedestrian traffic and low vehicle volumes compared to the other scenarios analyzed for the case study. The second model analysis in Chapter 4, Section 4.2.2 was done using these volumes.

TABLE B-2: Individual vehicle delays as modeled by Synchro

Offset (sec) Master intersection- Node 1	Signal delay (node 1) EB (sec/vehicle)	WB	Signal delay (node 2) EB (sec/vehicle)	WB	Signal delay (node 3) EB (sec/vehicle)	WB	Signal delay (node 4) EB (sec/vehicle)	WB	Signal delay (node 5) EB (sec/vehicle)	WB
0	14	9	8	11	10	10	11	8	9	14
2-->5, 3-->10, 4-->15, 5-->20	14	16	5	12	5	17	6	12	6	14
2-->10, 3-->20, 4-->30, 5-->40	14	16	7	16	7	17	7	17	7	14
2-->15, 3-->30, 4-->45, 5-->0	14	22	10	23	10	22	10	23	10	14
2-->20, 3-->40, 4-->0, 5-->20	14	27	12	27	13	27	13	27	13	14
2-->25, 3-->50, 4-->15, 5-->40	14	23	15	23	16	23	16	23	16	14
2-->30, 3-->0, 4-->30, 5-->0	14	19	19	19	19	19	19	19	19	14
2-->35, 3-->10, 4-->45, 5-->20	14	16	23	16	23	16	23	15	23	14
2-->40, 3--20, 4-->0, 5-->40	14	13	27	13	27	13	27	12	13	14
2-->45, 3-->30, 4-->15, 5-->0	14	10	23	10	22	10	22	10	22	14
2-->50, 3-->40, 4-->30, 5-->20	14	7	17	7	17	7	16	7	16	14
2-->55, 3-->50, 4-->45, 5-->40	14	5	12	5	17	5	12	5	16	14

The individual vehicle delays shown in Table B-2 for low vehicle volumes are observed to be lower compared to the corresponding delays in Table 4-2 for high vehicular traffic.

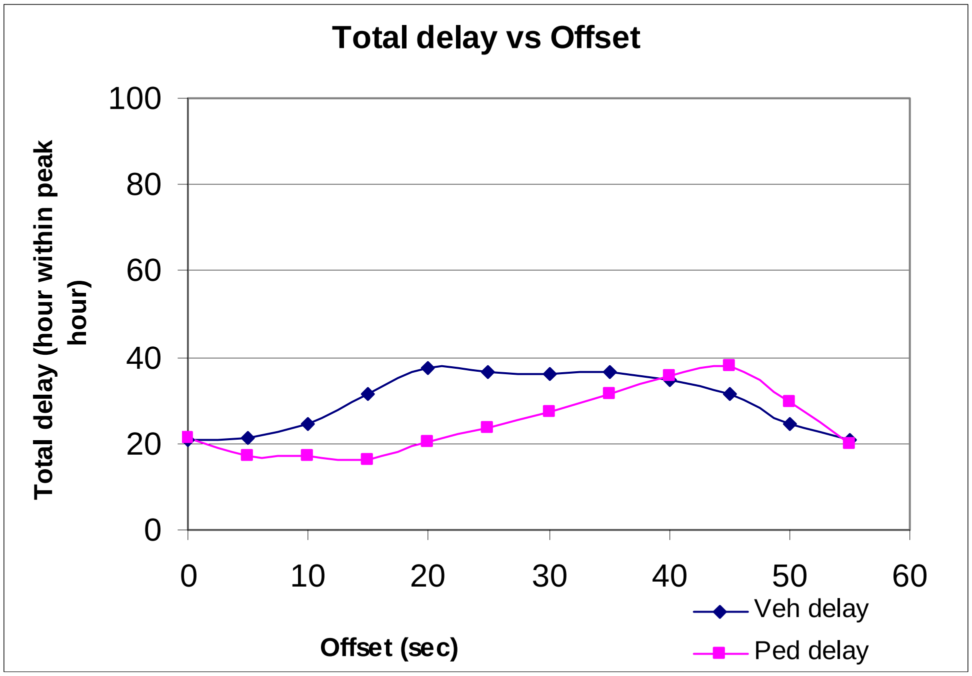


FIGURE B-1: Variation of total delay to pedestrians and vehicles with offset

Comparison of the total delay curves for pedestrians and vehicles in Figure B-1 shows that there is no significant difference in the range of delay for the two curves. This is unlike the situation in Figure 4-3 where the total delay to vehicles is significantly higher than that to pedestrians, probably because the vehicle volumes are relatively higher.

TABLE B-3: Determination of user costs for various offsets

Offset (sec) Master intersection-Node 1	Total delay to vehicles (hr within peak hr), Da	Total delay to pedestrians (hr within peak hr), Dp	Value of vehicle time, T_a \$/hr	Value of pedestrian time, T_p (\$/hr)	Average vehicle occupancy	User cost for vehicles and peds (\$/hr)
0	20.8	21.328	1.396	2.792	1.22	94.972
2-->5, 3-->10, 4-->15, 5-->20	21.4	17.288	1.396	2.792	1.22	84.714
2-->10, 3-->20, 4-->30, 5-->40	24.4	16.928	1.396	2.792	1.22	88.819
2-->15, 3-->30, 4-->45, 5-->0	31.6	16.288	1.396	2.792	1.22	99.294
2-->20, 3-->40, 4-->0, 5-->20	37.4	20.408	1.396	2.792	1.22	120.675
2-->25, 3-->50, 4-->15, 5-->40	36.6	23.648	1.396	2.792	1.22	128.359
2-->30, 3-->0, 4-->30, 5-->0	36	27.288	1.396	2.792	1.22	137.500
2-->35, 3-->10, 4-->45, 5-->20	36.6	31.548	1.396	2.792	1.22	150.416
2-->40, 3--20, 4-->0, 5-->40	34.6	35.870	1.396	2.792	1.22	159.077
2-->45, 3-->30, 4-->15, 5-->0	31.4	37.861	1.396	2.792	1.22	159.187
2-->50, 3-->40, 4-->30, 5-->20	24.4	29.695	1.396	2.792	1.22	124.464
2-->55, 3-->50, 4-->45, 5-->40	21	19.850	1.396	2.792	1.22	91.187

The key points of the data tabulated in Table B-3 are illustrated in Figure B-1 and Figure B-2. The lowest user cost does not correspond to the same offset as the lowest total vehicle delay or total pedestrian delay. Offsets are same for the greatest user cost and greatest total pedestrian delay.

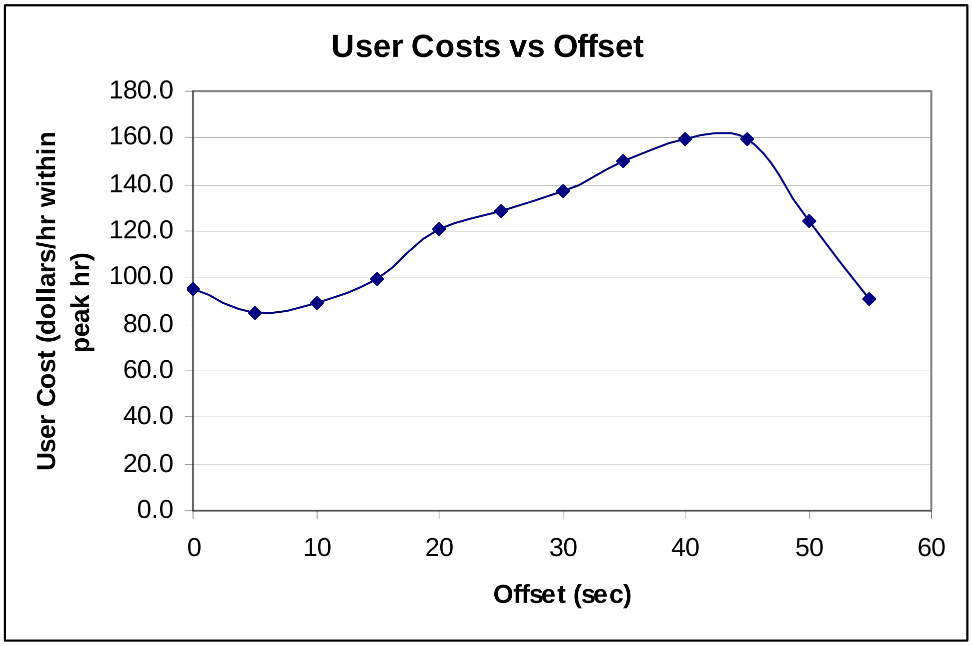


FIGURE B-2: Variation of user costs with offset

There is significant variation in user cost with different offsets, as observed from Figure B-2. Thus, even during low traffic volumes, if pedestrian volumes are high, signal coordination yields socio-economic benefits to travelers in the network.

SCENARIO 2: (in Section 4.2.2)

The objective of the case study in Section 4.2.2 was to observe delays and compare user costs for varying pedestrian volumes. Accordingly, the vehicle data remained the same and the pedestrian volumes changed for three traffic scenarios tested using Synchro. Three traffic scenarios with the same vehicle data and three sets of pedestrian volumes were modeled and analyzed. Two of these scenarios with the same vehicle volumes and different pedestrian volumes have already been described in Section 4.2.1 and Section 4.2.2 respectively. The results of the third scenario with the same vehicle demand and a different pedestrian volume are shown in Figure B-3 and Figure B-4.

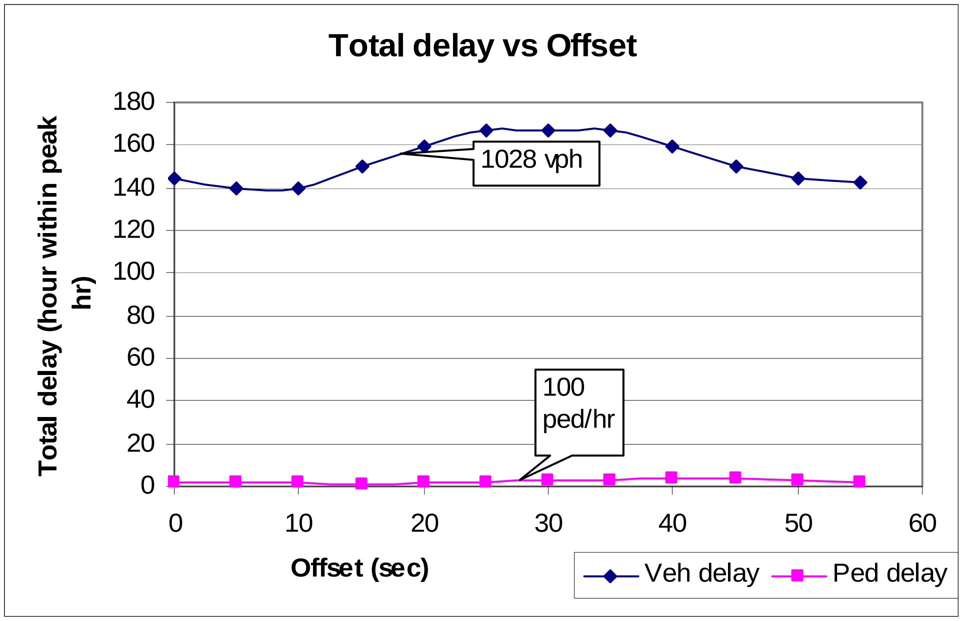


FIGURE B-3: Comparison of total pedestrian delay and total vehicle delay for various offsets for the third traffic scenario

The total delays to pedestrians with different offsets are significantly lower than the values illustrated in Figure 4-3 in Section 4.2.1 where pedestrian volumes are much higher. However, though the vehicular volumes are similar to the case study in Figure 4-3, the total delays to vehicles are also observed to be much lower in comparison to those in Figure 4-3.

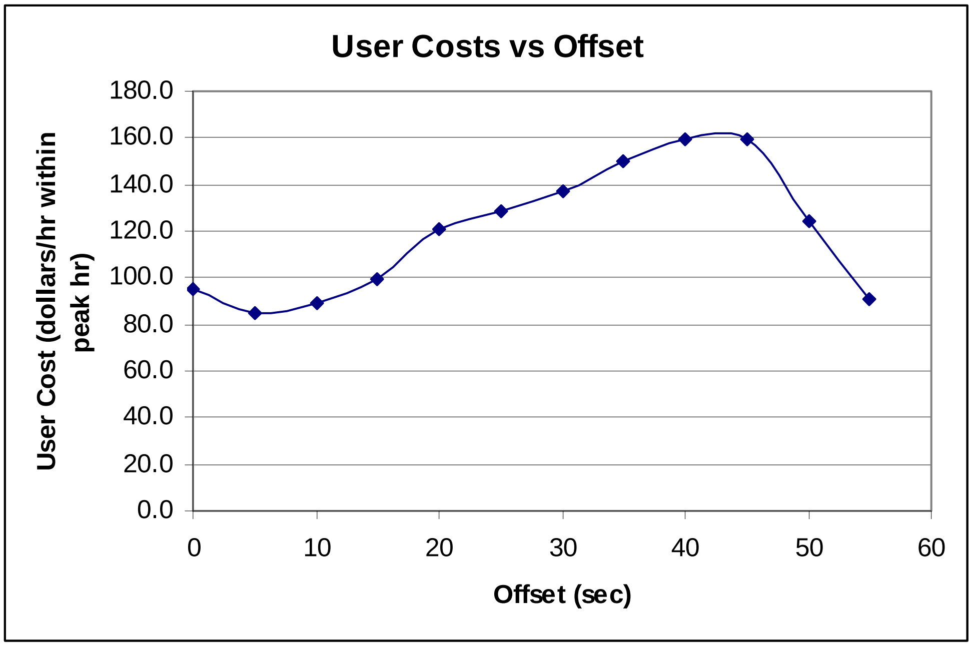


FIGURE B-4: User costs with various offsets for 100 pedestrians per hour

The user cost curve as depicted in Figure B-4 shows significant variation in the cost with different offsets. It is not significantly different from the user cost curve (pedestrians and vehicles) in Figure 4-4 in terms of variation in user cost between offsets.

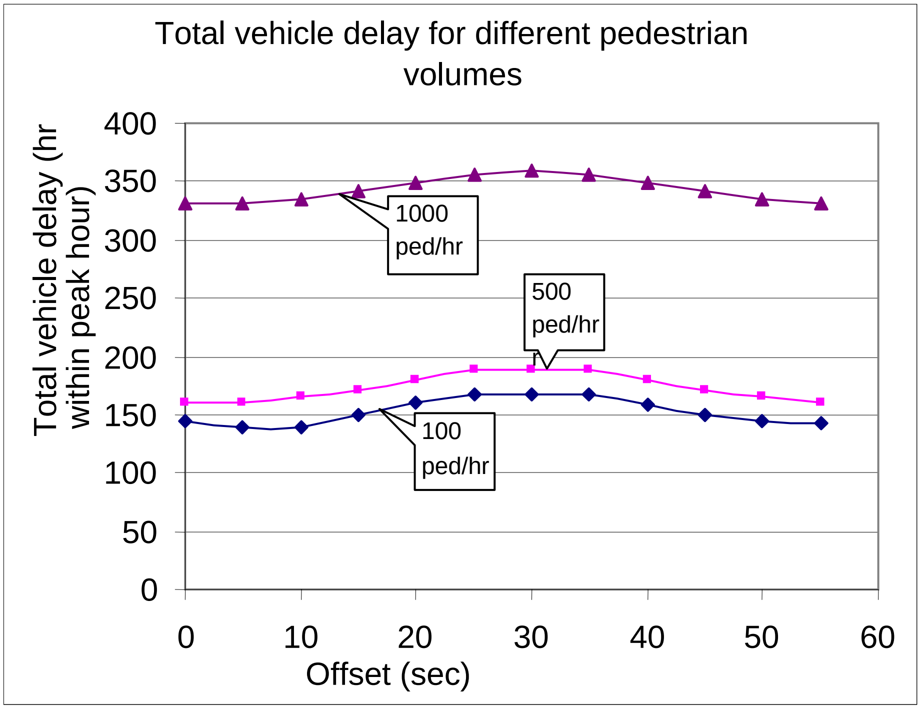


FIGURE B-5: Effect of increasing pedestrian volumes on vehicle delay for different offsets

The vehicle delay curves for the three pedestrian demand levels in Figure B-5 denote the effect of pedestrians on vehicle progression. The delay curve for the highest pedestrian volume among the three scenarios shows a distinct peak delay. The other two curves do not display a similar prominent peak. A low pedestrian volume of 100 pedestrians per hour results in the least vehicle delay for all offsets.

SCENARIO 3: (discussed in Section 2.1.2)

In Section 2.1.2, a significant observation on vehicle progression with increase in demand and vehicle congestion is formulated by modeling and analysis on Synchro. This observation is illustrated in Figure 2-5. The vehicle volumes were increased in steps to change the volume to capacity (v/c) ratio by small measures. Various offsets were applied for the analysis of each volume dataset. The volumes of the through vehicles on the major street were increased to change the volume to capacity ratio keeping volumes for all other movements fixed. The network conditions remained same throughout the analysis excepting the volumes. The flow conditions existing during the study are described as below.

Flow conditions

- Cross-street traffic has volume to capacity ratio (v/C) = 0.99
- Arterial traffic volume to capacity ratio varies with the through volume.
- Green to cycle ratio is constant for the movements.

The results of the analysis and related computations are shown below accordingly.

Results

The delay ratios were computed for each volume scenario. The delay ratio is the ratio of the minimum delay among all the offsets to the average delay for all offsets. Table B-4 tabulates the results for each volume and shows the delay ratio corresponding to each v/C ratio. It is evident from the table that the delay ratio varies with the v/c ratio.

TABLE B-4: Computation of delay ratio for increasing v/C ratios

(Figure 2-5 in Section 2.1.2 is based on this table)

Volume (EB Th & WB Th) (vph)	v/C ratio	Average delay (best offset) (A1)(sec/veh)	Average delay (all offsets) (A2)(sec/veh)	Delay Ratio (A1/A2)
485	0.5	5.6	9.733	0.58
590	0.6	5.5	10.2	0.54
660	0.7	6.1	10.792	0.57
745	0.8	9.4	13.925	0.68
840	0.9	16.8	21.242	0.79
935	1	58.6	62.75	0.93
980	1.05	157.6	161.533	0.98
1025	1.1	181.4	185.133	0.98
1075	1.15	197.5	201.05	0.98
1120	1.2	204.4	207.85	0.98

The data from Table B-4 was utilized to plot the curve in Figure 2-5 in Section 2.1.2. The benefits of providing signal coordination to vehicles supposedly diminish with increasing vehicle congestion. The objective of this particular analytical study was to verify the reasonableness of this supposition. Accordingly, Figure 2-5, in Section 2.1.2, based on the study result supports the theory.